Report of the DESDynI Applications Workshop

October 29–31, 2008
UC Sacramento Conference Center

April 23, 2009. Version 1.

April 23, 2009

Dear Colleague,

In 2007 The National Research Council Earth Science Decadal Survey, Earth Science Applications from Space, recommended a five-year integrated L-band InSAR and multibeam Lidar mission called DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice) be launched in the 2010–2013 timeframe. The mission will measure surface deformation for solid Earth and cryosphere objectives and vegetation structure for understanding the ecosystem structure and carbon cycle.

Because there are numerous applications that DESDynI can address NASA convened a workshop in October 2008 to address to discuss these applications and related data products. Identified applications include monitoring of earthquakes, volcanoes, landslides, ground subsidence, floods, glacier surges and ices sheet/shelf collapse, wildfires, hurricane/cyclone damager, riparian vegetation for fish habitats, wind events, oil spills, beetle infestations, and surface deformation associated with subsurface reservoirs and CO_2 sequestration. In certain configuration DESDynI could also address soil moisture, fire extent, coastal oceans, and ocean currents.

The primary objective of the workshop was to further develop the applications goals and objectives, and traceability to needed observations and measurements. Numerous people contributed extensively to both the workshop, as indicated in Appendix and to to this report including the organizing committee listed below. Other contributors include Craig Dobson, Jeanne Sauber, Mahta Moghaddam, Elijah Ramsey, Ben Holt, Ronald Blom, Brian Huberty, Margaret Glasscoe, Pablo Clemente-Colón, and Ben Brooks. It is our intention to make this a living document and update it as the mission and new techniques and methodologies are developed. The level of participation in both the workshop and writing of this report indicates the great interest and importance of addressing numerous applications with the DESDynI Mission.

Sincerely yours,

Andrea Donnellan, Gerald Bawden, and John Rundle
Workshop Conveners

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Organizing Committee

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Executive Summary

Spaceborne technologies provide data of the Earth that are of utility for improving scientific knowledge as well as for providing information for operational applications. The data become of greater utility for applications as the observations and/or scientific understanding is improved. In 2007, following a request from NASA, NOAA, and the USGS the National Research Council published a report entitled "Earth Science Applications from Space: A Community Assessment and strategy for the future," better known as the Earth Science Decadal Survey [1]. The decadal survey group was to generate consensus recommendations from the science and applications community for a systems approach to conducting space-based and ancillary observations that address both the research and operational communities. The report recommended 17 missions, including a mission called DESDynI (Deformation, Ecosystem Structure, and Dynamics of Ice), which was recommended for launch in the first tier of four missions. DESDynI is five-year L-band InSAR and Multibeam Lidar mission with objectives to:

1. Determine the likelihood of earthquakes, volcanic eruptions, and landslides.
2. Predict the response of ice sheets to climate change and impact on sea level.
3. Characterize the effects of changing climate and land use on species habitats and carbon budget.
4. Understand the behavior of subsurface reservoirs.

Meeting these multidisciplinary objectives requires systematic scientific research, but each of these goals includes applications related to the societal impacts of the phenomena that are being studied. In addition, then, to the systematic science that DESDynI will achieve, there are numerous applications that DESDynI can address including measurement, monitoring, and response to earthquakes, volcanoes, landslides, ground subsidence, floods, glacier surges and ices sheet/shelf collapse, wildfires, hurricane/cyclone damage, riparian vegetation for fish habitats, wind events, oil spills, beetle infestations, and surface deformation associated with subsurface reservoirs and CO_2 sequestration. In certain configurations DESDynI could also address soil moisture, fire extent, coastal oceans, and ocean currents. This workshop addressed specifically the various applications components of DESDynI and related data products. Experience with prior NASA missions indicates that pioneering new technology such as DESDynI will indeed foster new, efficient, and productive applications, and a goal of this workshop was to anticipate some of these while the sensors and mission are still being designed.

The primary objective of this workshop was to identify and catalogue the potential of DESDynI related applications goals and objectives, and their traceability to desired observations and measurements. NASA will consider the application needs that DESDynI can address along with the science requirements identified by NASA under a separate activity. These will inform NASA on the design concept of DESDynI, thereby enhancing the likelihood that the mission will provide rapid and useful applications and response products.

There were over 50 participants in the workshop and five contributed posters from the broader community. Attendees included representatives from NASA HQ, NASA Goddard Space Flight Center, Jet Propulsion Laboratory, NASA Ames, NOAA, US Geological Survey, Department of Energy, State of California, USDA National Forest Service, University of California, and DLR – the German Aerospace Center. There was significant participation by first responders. One important outcome of the meeting was that no new instruments or modes were requested for the DESDynI mission. The needs for the applications enumerated at the workshop mainly impact the duty-cycle, downlink capacity, and data latency for SAR/InSAR as well as generation of high-level products for both SAR/InSAR and multibeam lidar. Future workshops can be used to more clearly define participants from the applications community as well as to identify any additional commitments that may be needed to meet the applications goals. Specific questions were asked of the workshop participants during breakout sessions and disciplines were divided into these four areas:

1. Geohazard Assessment and Response
2. Floods, Oceans, and Coastal Applications
3. Subsurface Reservoirs
4. Forest and Ecosystems Management

This workshop is a starting point for community engagement and is intended to identify those applications of high societal benefit and with high probability of success. The workshop focused on identifying the goals and objectives for each application, the observational needs, the desired data products, targets of interest, and response plans.

Applications in the Context of DESDynI

DESDynI can provide unique observations of surface deformation and ecosystem structure. It can also be used to provide imagery for various events such as floods or wildfires. As a result, there are a number of applications that DESDynI can address if configured properly (Table 1). The science drivers for DESDynI provide a basic set of requirements, which when factored into the mission design and configuration lead to improved science understanding. This improved understanding is essential for better addressing the related applications. The science and applications are intertwined such that science advances improve the utility of the technology and methodology for the application. Improving the scientific understanding of the hazard related applications should mitigate damage and losses from events associated with them.

Table 1. Applications relevant to DESDynI by discipline. White shading indicates substantial overlap with DESDynI science measurements and objectives, gray boxes indicate additional applications and needs. Checkered boxes are relevant to both science and applications, but the applications have additional needs such as shorter turnaround for data products compared to the science needs.

Geohazard Assessment and Response	Floods, Oceans, and Coastal Applications	Subsurface Reservoirs	Forest and Ecosystems Management
Earthquakes	Floods	Hydrology of aquifer systems	Biomass and vegetation structure
Volcanoes	Coastal wetlands and adjacent resources	Hazard mitigation	Ecosystem health and management
Landslides	Oceanic and coastal water applications	Water resource management	Biodiversity of plants and animals
Systematic measurements	Ice and navigation	CO_2 Sequestration	Disturbance of natural ecosystems
Mitigation			
Response			

Goals, Objectives, and Observation Needs

The applications goals for DESDynI address understanding risk and hazards for geohazards, oceans, and hydrological applications, and understanding changes, impacts, and causal factors for subsurface reservoirs, forests, and ecosystems (Table 2). For applications DESDynI can be used to monitor and characterize changes. The results can be used to mitigate losses from hazards and ecological changes, protect infrastructure, and reduce economic impacts.

Table 2. Goals and objectives for each discipline.

Discipline	Goals	Objectives
Geohazards	Understand the risk from earthquakes, volcanoes, and landslides to reduce the loss of life and property.	Characterize the hazards of earthquakes, volcanoes, and landslides.
Hydrological and Ocean Applications	Minimize hazards and understand the impacts on ecosystems, habitability, and navigation from floods, coastal oceans, and sea and lake ice cover.	Characterize the status and trends of floods, coastal oceans, and ice.
Subsurface Reservoirs	Assure integrity and understand the impacts of changing subsurface aquifers, reservoirs, and C02 sequestration.	Predict subsurface reservoir properties and determine the response to changes in input and stress.
Forest and Ecosystems Management	What is the spatial distribution of carbon fluxes and can they be linked to specific causal factors, such as disturbance or climate change?	Characterize terrestrial ecosystems with respect to biomass, biodiversity, and disturbance/change through time.

Generally, for applications a more rapid response is required compared to that required for meeting the science goals. In most cases achieving the science goals requires the data, but not necessarily quickly. DESDynI is being designed to address improved understanding of the processes related to geohazards, subsurface reservoirs, and ecosystems, which encompasses the science and applications. Specific applications may levy additional requirements if they are to be addressed by the DESDynI Mission. Addressing floods, oceans, and coastal applications with DESDynI would levy substantial new drivers on the mission (Table 3), impacting data rates, duty cycle, and costs. Rapid turnaround of the data and data products would also impact the costs of the mission.

Table 3. Applications needs that have not been identified under the science requirements for DESDynI.

Need	Impacted Applications	Comment
Quick look products	• Earthquakes • Volcanoes • Landslides • Floods • Blowdowns • Coastal storms	• For response • Lower latency is more important than data quality • Signals from damaging events are usually much larger than the errors
Low latency between event and data retrieval	• Earthquakes • Volcanoes • Landslides • Floods • Blowdowns • Coastal storms • Wildfires	• Would be improved by a cooperative international constellation
US focus with greater observational coverage	• Particularly for subsurface reservoirs and aquifers • Coastal and lake regions, including over water	• These applications aren't covered under the science objectives • Coastal and lake regions were not identified by the decadal survey as part of DESDynI

DESDynI Data Products and Required Ancillary Data

The applications data products required from DESDynI are similar to those required to meet the science goals of the mission (Table 4). There are additional coverage goals for observing aquifers, reservoirs, and coastal oceans and flooding. The data latency, however, is much lower than that required for the science observations, particularly for hazard response. Emergency responders would benefit from quick-look products, even if they have degraded accuracy or resolution. The data products also need to be accessible and easily ingestible into other analysis systems. Web services with a clear workflow are recommended.

Table 4. DESDynI data products and required ancillary data.

Instrument	Data Product
DESDynI	*All data should be georeferenced*
Lidar	
Elevation profiles	Digital Elevation Model (DEM) for precise elevation maps
	Sea ice thickness
Waveform fused with SAR	Aboveground biomass at 1 hectare resolution
Waveform	Vertical vegetation structure to ±1m
Radar	
Interferograms	3D time dependent vector surface deformation
Permanent scatters	2D/3D time dependent surface motions, sea ice motion
Polarimetric SAR/InSAR	Aboveground biomass
Backscatter	Coastal winds, biomass, oil slicks/seeps
SAR/InSAR	Landscape heterogeneity
SAR coherence	Forest disturbance maps
Ancillary Data	
GPS	Plate Boundary Observatory (PBO) and other existing deformation maps
Leveling	Precise vertical control
Seismic	Earthquakes, including location, size, and mechanism
Gravity	To understand subsurface anomalies and changes
Geologic data	Fault locations and rock types
Hydrologic data	Pore-fluid pressures/water-level data
Weather	Conditions at time of acquisition
Optical Imagery	Flood extent, ecological characteristics

Monitoring and Event Response Plan

The applications community in each sub-discipline has a need for systematic monitoring to establish baselines, characterize each application area, and assess temporal variability. Monthly measurements are typically acceptable for the systematic monitoring unless the variability is on a timescale faster than that. More frequent systematic monitoring on weekly timescales would enable forecasting or assessment of forecasting capability. Measuring surface deformation, along with other observations such as seismicity, is important for earthquake prediction. Pre-slip before landslides has also been observed. There are some suggestions in the literature of increased strain prior to earthquakes, and DESDynI will be an ideal tool for characterizing surface strain prior to earthquakes. This would require a rapid repeat interval in deforming regions.

There are numerous events that can occur, which require rapid response. Ideally, the response time would be on the order of 1–4 days, which minimum weekly measurements for several months following the event, or until the region returns to its background condition. Such events include, but are not limited to, earthquakes, volcanoes, landslides, floods, wildfires, coastal inundation, reservoir leaks, or sudden injection or withdrawal of fluids due to enhanced recovery.

The systematic monitoring requirements for applications are consistent with those for science. The response needs have a much shorter latency requirement. The data are required at some point in order to address the science aspects of the application, however, for response and recovery the data must be quickly available. Quick look products with lower resolution and accuracy are more important than precise products that are delivered after the recovery has occurred.

Targets and Observational Frequency

Addressing the applications needs requires observations across the United States. Earthquakes, volcanoes, and to some extent landslides are all associated with and occur most frequently within actively deforming regions. Landslides occur where there are slopes, and large earthquakes can occur in intracontinental regions. The major targets for subsurface reservoir observations include the major continental sedimentary basins and hydrologic basins where fluid withdrawal or injection can result in surface deformation. Other major basins may include polar and permafrost regions where land use changes may trigger or accelerate surface deformation. The observation target for forest and ecosystem management is the global distribution of vegetated surfaces, including the surrounding transition zones required to capture encroachment or degradation.

Rapidly deforming regions should be observed frequently on weekly timescales, but a baseline set of observations should at minimum be collected for all of the landmasses at the beginning and end of the mission. Yearly to sub-yearly measurements are required for the US and for the remaining intracontinental regions as observing scenarios allow. The highest priority coastal collections include the entire U.S. Gulf coast, specifically the Mississippi Delta region, the Florida everglades, the Delmarva Peninsula, Washington's Puget Sound, the Aleutian Islands, Hawaii, and urban centers situated near the coast such as New Orleans. In general ecosystems applications require seasonal observations.

Disasters and other hazard related events should be observed during the next available pass of DESDynI and during all subsequent passes in which rapid change is occurring. The timescale of change may be weeks to months. Events include, but are not limited to, earthquakes, volcanoes, landslides, hurricanes, wild fires, storm surges, floods, wind events, and oil spills.

Recommendations

In addition to the preliminary definition of requirements (desirements) for the DESDynI mission to meeting applications needs, there were several recommendations that came out of the workshop.

Workshop Follow-On Activities

1. Establish an interagency working group to explore potential roles and responsibilities for DESDynI.

2. Vet this document with the wider community

3. Allow for further iteration of potential observation requirements, data/information products, and temporal and spatial sampling throughout the course of the DESDynI concept development.

4. Create a WiKi to house necessary documents.

5. Develop an understanding of how DESDynI fits into GEOSS.

6. Explore opportunities to prototype DESDynI applications using available streams of spaceborne and airborne L-band SA/InSAR and LiDAR data.

7. Prepare for follow-on applications meeting. Explore whether this should be combine with other applications workshops in the planning stages, such as SMAP.

Mission Configuration

1. Establish a capability for rapid downlink and dissemination of quick-look data products for event response and recovery.

2. Develop end user products for decision support.

3. Establish an open data policy to enable broad usage.

4. Enable DESDynI as a US contribution to international collaborations.

1. Geohazard Assessment and Response

The National Science and Technology Council Subcommittee on Disaster Reduction calls for our nation to provide hazard and disaster information where and when it is needed [2]. It states that we need to understand natural processes that produce hazards, develop hazard mitigation strategies and technologies, and assess disaster resilience using standard methods. The new observations provided by DESDynI, coupled with improved modeling capability, will advance fundamental understanding of the nature of earthquakes, volcanoes, landslides, and other hazards. These advances will enable the science community to better forecast these geohazards and enable the development of mitigation strategies by hazard planners. DESDynI is primarily a systematic science mission; however, it can be used to address such a diversity of hazards, listed below, that it could be in continual response mode following events. Therefore, it is important to understand the priority of observing such events based on geographic location, size of event, potential impact of event and the need to rapidly respond following the event. The U.S. Subcommittee on Disaster Reduction (SDR) is an element of the President's National Science & Technology Council charged with:

- Establishing clear national goals for Federal science and technology investments in disaster reduction;
- Promoting interagency cooperation for natural and technological hazards and disaster planning;
- Facilitating interagency approaches to identification and assessment of risk, and to disaster reduction; and
- Advising the Administration about relevant resources and the work of SDR member agencies.

The objective is to enhance disaster resilience by composing a ten-year agenda for science and technology activities that will produce a dramatic reduction in the loss of life and property from natural and technological disasters. DESDynI can feed into that agenda by providing information for geohazard assessment and response. The DESDynI mission addresses in various ways the grand challenges identified for disaster reduction (http://www.sdr.gov):

Challenge: Provide hazard and disaster information where and when it is needed:

"To identify and anticipate the hazards that threaten communities, a mechanism for real-time data collection and interpretation must be readily available to and usable by scientists, emergency managers, first responders, citizens, and policy makers.

Developing and improving observation tools is essential to provide pertinent, comprehensive, and timely information for planning and response."

"Warn the right people in the right place at the right time."

Understand the natural processes that produce hazards

> *"To improve forecasting and predictions, scientists and engineers must continue to pursue basic research on the natural processes that produce hazards and understand how and when natural processes become hazardous.*
>
> *New data must be collected and incorporated into advanced and validated models that support an improved understanding of underlying natural system processes and enhance assessment of the impacts."*
>
> *"Continuous and useful information about the hazard must be available to everyone affected."*

Develop hazard mitigation strategies and technologies

> *"To prevent or reduce damage from natural hazards, scientists must invent— and communities must implement—affordable and effective hazard mitigation strategies, including land-use planning and zoning laws that recognize the risks of natural hazards. In addition, technologies such as disaster-resilient design and materials and smart structures that respond to changing conditions must be used for development in hazardous areas."*
>
> *"By designing and building structures and infrastructures that are inherently hazard resilient, communities can greatly reduce their vulnerability."*

Recognize and reduce vulnerability of interdependent critical infrastructure

> *"Protecting critical infrastructure systems, or lifelines, is essential to developing disaster-resilient communities. To be successful, scientists and communities must identify and address the interdependencies of these lifelines at a systems level (e.g., communications, electricity, financial, gas, sewage, transportation, and water)."*
>
> *"Protecting critical infrastructure provides a solid foundation from which the community can respond to hazards rapidly and effectively."*

<u>Assess disaster resilience using standard methods</u>

> *"Federal agencies must work with universities, local governments, and the private sector to identify effective standards and metrics for assessing disaster resilience. With consistent factors and regularly updated metrics, communities will be able to maintain report cards that accurately assess the community's level of disaster resilience."*
>
> *"Learn from each hazard event…to support ongoing hazard research and future mitigation plans."*

<u>Promote risk-wise behavior</u>

> *"Develop and apply principles of economics and human behavior to enhance communications, trust, and understanding within the community to promote 'risk-wise' behavior.*
>
> *To be effective, hazard information (e.g., forecasts and warnings) must be communicated to a population that understands and trusts messages. The at-risk population must then respond appropriately to the information."*
>
> *"This is an ongoing challenge that can only be met by effectively leveraging the findings from social science research."*

In February 2008, the SDR published 14 hazard-specific implementation plans. New plans will be authored as events dictate. The goal of developing these plans is to create a more disaster-resilient America in which: relevant hazards are recognized and understood; communities at risk know when a hazard event is imminent; property losses and lives at risk in future natural hazard events are minimized; and disaster-resilient communities experience minimum disruption to life and economy after a hazard event has passed.

DESDynI will provide a unique dataset, in the form of crustal deformation for understanding geohazards and in particular earthquakes, volcanoes, and landslides. These systematic observations of crustal deformation will provide information about the state of the Earth's surface and crust prior to events, as well as any response and possible triggered events after the occurrence of primary events.

1.1 Applications in the Context of DESDynI

1.1.1 Earthquakes

Earthquake science is a rapidly advancing field, but is observation-limited. The long repeat time for earthquakes results in few complete earthquake cycles observed at any location. Spatial coverage can substitute for temporal coverage by providing observations of hundreds of different earthquakes and faults at different parts of their cycle (Figure 1). At any one place, characteristic repeat times of earthquakes are hundreds to thousands of years. At any one time, earthquake related deformation is going on somewhere. Studies of events at one location provide understanding to apply elsewhere. Improved theory, seismic networks, experiments, and computational capabilities make the field ripe for an advance. Quantitative use of frequent observations of surface deformation would have a huge impact on both science and applications. Earthquake prediction is not imminent, but improved forecasting is attainable particularly with new datasets of global deformation and fault ruptures that missions such as DESDynI would produce. Better estimation of potential earthquake sources from these forecasts would improve risk assessment (Figure 2).

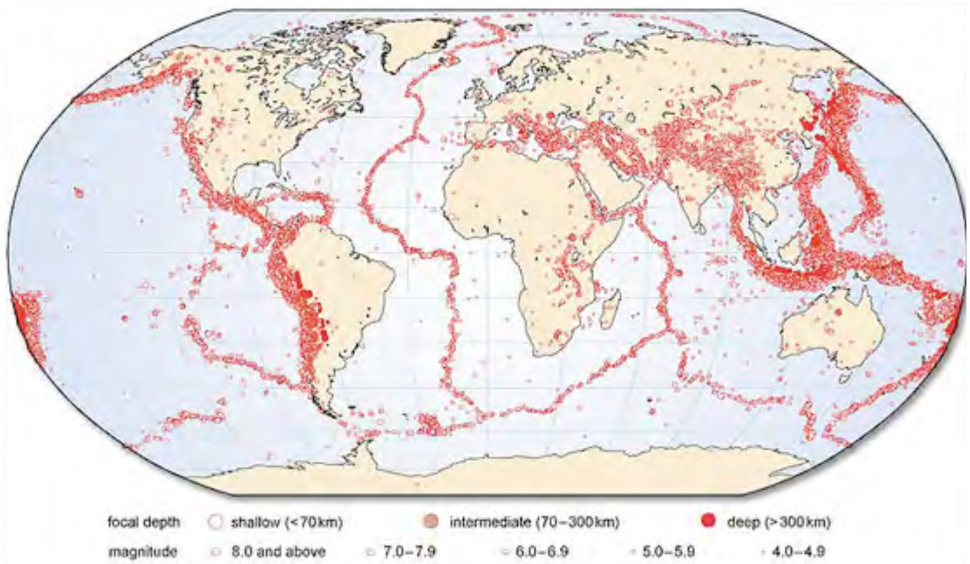

Figure 1. Global seismicity map. Over 1400 M>5 earthquakes occur globally each year. [USGS, 2009].

Figure 2. DESDynI will provide deformation (=> stress) variations throughout the earthquake cycle for earthquake risk estimation.

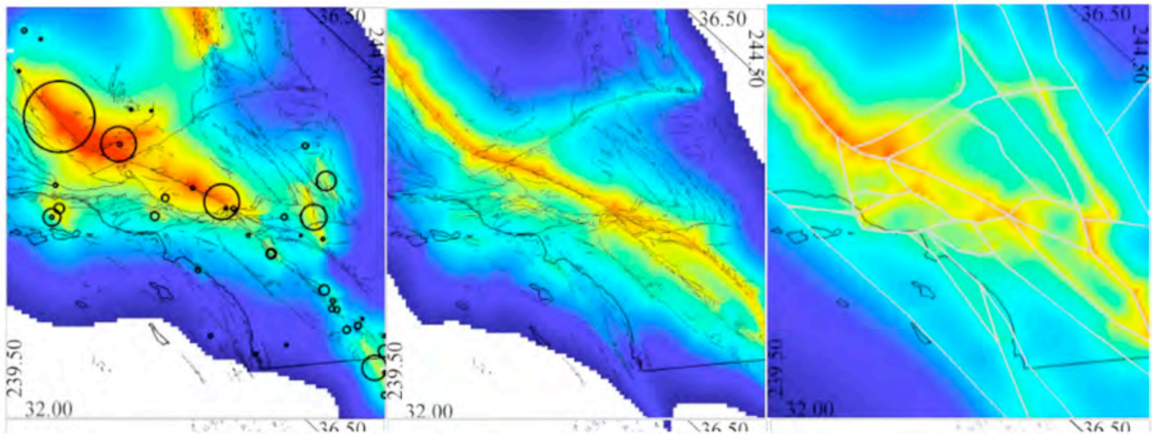

Figure 3. Left Panel: Coseismic displacement release, 1800-2000; Middle panel: Geologic estimate of displacement accumulation over the same time period; Right panel: Geodetic estimate of displacement accumulation which much more closely matches to coseismic displacement release.

Spatial variations in strain rate reflect earthquake probability variations. Inversion of surface deformation measurements provides insight into the fault geometry and seismic activity. Refinement of earthquake hazard maps allows for improved prioritization for retrofitting and risk mitigation (Figure 2). The geologic estimate of displacement accumulation and earthquake distribution is much more spatially uniform than the geodetic estimate of displacement accumulation, which much more closely matches the coseismic displacement release. Geodetic measurements of deformation should more accurately indicate the higher earthquake hazard regions (Figure 3).

One of the goals for improved earthquake forecasting is to understand interactions between faults. The system can be viewed like weather systems where each earthquake (storm) changes the state of the system. Observations from space have led to continuously improved skill at understanding these interactions over past decades. To understand seismic hazards we must determine the interseismic, preseismic, coseismic, and post-seismic strain variations. Earth's upper crust is primarily elastic, and the strain rates correlate with stressing rates. Spatial variations imply long-range earthquake hazard. Temporal variations imply intermediate and short-term hazard variations. We must derive models of faulting and rheology from vector displacements and assimilate the vector surface displacements into numerical models of fault systems. Currently we are data poor.

1.1.2 Volcanoes

InSAR has identified active volcanoes previously thought to be dormant and can be used for volcano assessment and monitoring. Measurement of deformation associated with volcanoes can be used to derive models of magma migration and pressure changes. An example of InSAR monitoring of a volcanic system is given in Figure 4. DESDynI can also be used to analyze the extent of the erupted material.

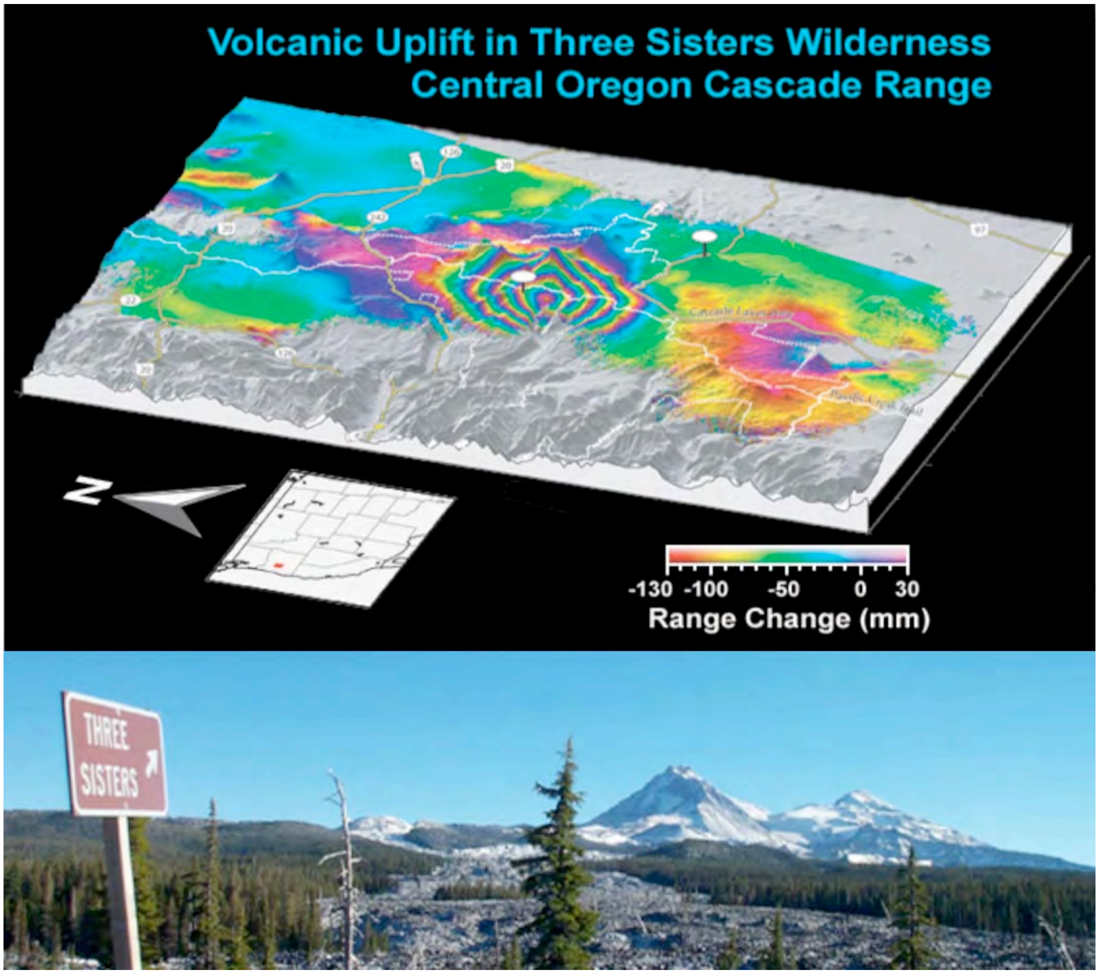

Figure 4. InSAR image of Three Sisters volcano (top) and photo (bottom)

1.1.3 Landslides

Both the lidar and radar instruments onboard DESDynI can provide detailed observation of down-slope movements from landslides. Recent work also indicates that it is possible to identify potential landslides as pre-slip before landslides are observable (Figure 5). This should lead to mitigation of losses from landslides. As noted on the U.S.G.S. landslide web page (landslides.usgs.gov), landslides constitute a major geologic hazard because they are widespread, occur in all 50 states and U.S. territories, and cause $1-2 billion in damages and more than 25 fatalities on average each year. Landslides typically occur in deformation regions, but have a more stringent resolution requirement. Data sets for studying landslides are comprised of a range of data including slope, soil and moisture conditions, precipitation, seismicity, and temperature (developed by the Norwegian Geotechnical Institute and UNEP-Grid Geneva). Deformation and altimetry measurements will indicate volume of material in the landslide potentially prior to occurrence and after landslides.

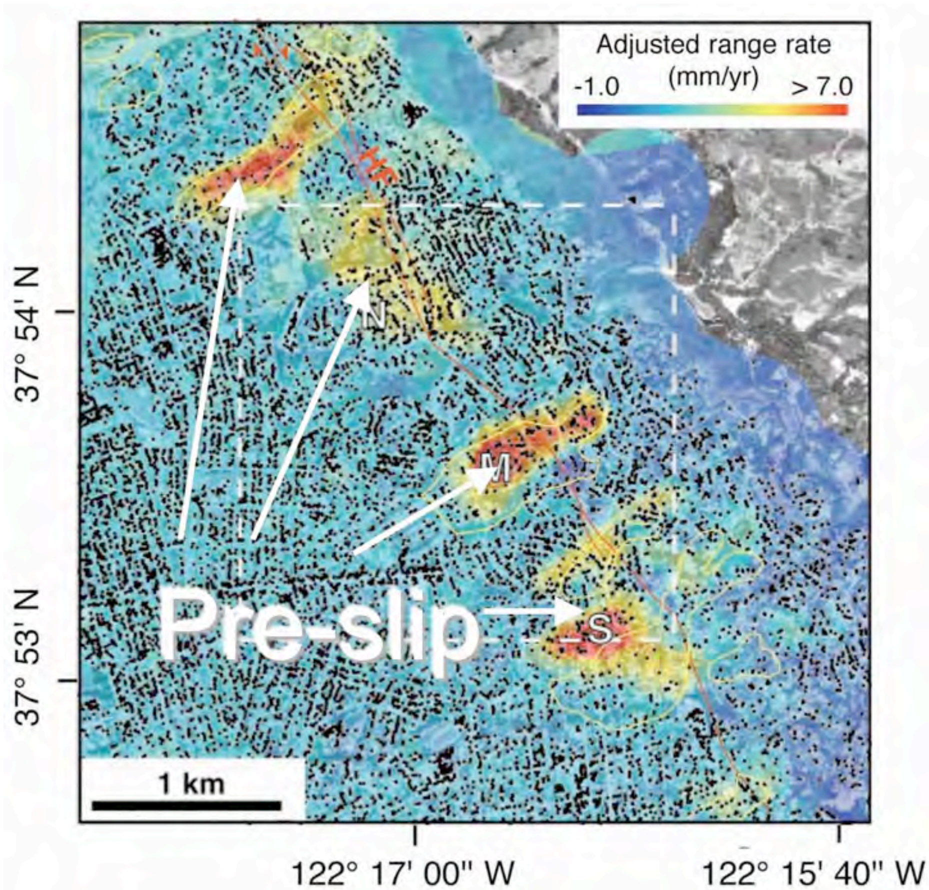

Figure 5. Potential landslides in the Berkeley Hills, California as indicated by preslip. (Courtesy Roland, Burgmann, UC Berkeley).

1.2 Goals, Objectives, and Observation Needs

The primary DESDynI mission goal, which is to *determine the likelihood of earthquakes, volcanoes, and landslides and quantify the magnitude of events*, meets both science and applications goals. The application goal is extended as follows:

1.2.1 Common Goals, Objectives and Observation Needs

Applications Goal: Understand the risk from earthquakes, volcanoes, and landslides to reduce the loss of life and property.

Applications Objectives: Characterize the hazards of earthquakes, volcanoes, and landslides.

Observation: Measure surface deformation

Measurements:

- Coverage of identified geohazard regions
- Baseline observations for global land surfaces
- 100 m imagery

- Horizontal deformation accurate to 1 mm/yr or 5% of the deforming zone
- Vertical velocities accurate to 2 mm/yr
- Imagery across the width of the deforming boundary

Observation: Measure surface disruption

Measurements:

- 20 m resolution imagery
- 400 m zone beyond the disrupted surface

Observation: Measure vertical change of the disrupted surface

Measurements:

- One baseline measurement over geohazard regions
- One measurement following a detectable event
- 10 cm vertical precision
- 25 m horizontal resolution

Measurement of crustal deformation coupled with models will identify potentially hazardous regions or the hazard, which is the probability of occurrence of an event. This can be used to identify high risk areas. Risk is the potential impact of the event, which is related to the hazard and the exposure.

1.2.2 Earthquakes

Historically, there have been on average 16 major earthquakes per year with 7 of those resulting in deaths. Therefore, over a five-year mission, given the assumption that Earth's landmasses will be observed with DESDynI and baselined at the beginning of the mission, we can expect DESDynI to observe about 78 major earthquakes with 38 of them resulting in deaths. In addition to making contributions to understanding the coseismic and postseismic slip associated with these major events, DESDynI will constrain strain rates that can be used to assess earthquake hazard and aftershock likelihood for a given region. The following scientific objectives and parameters are needed for assessing and mitigating earthquake hazard and risk:

Improved forecasting time scale

DESDynI will shorten forecasting timescales through the measurement of interseismic strain rates and/or surface creep. The estimates of surface deformation (strain and creep) will feed into 3D models of fault behavior. The frequent observations that DESDynI will provide will allow for observations of temporal variation in strain rate. This may lead to short-term prediction of earthquakes.

Response and recovery following a large earthquake

DESDynI data will be used to support response and recovery efforts following large earthquakes. Polarimetric imagery, decorrelation maps, and surface disruption observations will be used for damage characterization. Observation of strain rates will be coupled with models to assess the potential for triggered events and large aftershocks.

Other applications associated with earthquakes

DESDynI data will be used to understand the relationship between earthquakes and other processes such as:

- Slow slip events and slow earthquakes
- Landslides triggered by earthquakes
- Evaluation of the relationship between volcanic eruptions and earthquakes (Manga and Brodsky, 2006)
- Identifying of "blind" earthquake sources from surface deformation (InSAR) and/or structure geometry (Lidar)
- Differentiation of strain between tectonic and other processes [3]

1.2.3 Volcanoes

On average, there are about 71 major volcanic eruptions per year. That means that over the course of the five-year mission, DESDynI will observe over 350 eruptions. The mission will also be used to provide a baseline measurement of all volcanoes globally to determine which of those are actively deforming. Previous InSAR work has identified actively deforming volcanoes, which were previously thought to be dormant in both North and South America. The scientific objectives and parameters needed for volcano studies are similar to those for earthquake studies and forecasting.

Short-term prediction

Short-term volcanic eruption prediction is more advanced than earthquake prediction. Magma movement within the chambers triggers seismic activity and often observable surface deformation. From observations of seismic activity and surface deformation the hazard and risk can be estimated. Temporal variations in surface deformation might provide an indication of the forecast time scale.

Response and Recovery

DESDynI as well as UAVSAR will provide detailed imagery for characterizing damage from volcanic eruptions. This includes deposit volume, thickness, and distribution of the eruption, changes in volcano morphology, and measurements of plume characteristics. Imagery will be in the form of polarimetric radar, backscatter, decorrelation, and InSAR. [4]

Measurement Needs

Needs, which are cross-cutting, are outlined before the specific hazards are discussed.

- Global survey of volcanoes at beginning of mission
- Two "observations" spaced 3–6 months apart to detect deformation
- Frequent monitoring of active volcanoes

- One “observation” per year for remaining volcanoes
- Strip map for eruptions (ScanSAR for broadly deforming volcanoes)

1.2.4 Landslides

The total land area subject to landslides is about 3.7 million km^2, which occur in all 50 states. Severe storms, earthquakes, volcanic activity, coastal wave action, and wildfires can cause widespread slope instability [USGS Landslide Web site, 2009]. To address landslide hazards, several questions must be considered: Where and when will landslides occur? How big will the landslides be? How fast and how far will they move? What areas will the landslides affect or damage? How frequently do landslides occur in a given area? Typically, landslides occur in deforming regions, but the resolution requirement is more stringent, because the affected area is generally much smaller.

Inventory of active landslides

DESDynI can be used to inventory active landslides in the US and key global regions by measuring surface motions associated with slopes over time. This will feed into hazard and risk assessment and short-term prediction. Assessment will be improved by measurements of moisture either from DESDynI or other missions such as SMAP (Soil Moisture Active Passive). DESDynI should also be used to understand temporal variations in surface deformation, which should provide insight into possible forecasting timescales. As for earthquakes and volcanoes, polarimetric imagery and decorrelation maps can be used to characterize damage immediately following the event. Lidar and radar should also be used to determine changes in slope morphology as well as characterize landslides [5].

1.3 Specific Return and Unique Measurements from DESDynI

DESDynI will provide US directed systematic measurement of priority sites for meeting science and applications objectives. The mission will provide a higher frequency of observations than existing SAR and Lidar missions. The systematic higher frequency measurements will provide time varying information of geohazard processes. The ascending, descending, and left and right radar views will enable 3D vector determination of motions. Coupling the observables with models and simulations will provide insight into geometry, mechanisms, and spatial and timescales of geohazard processes. The simultaneous InSAR and lidar measurements can be used to better constrain processes such as volcanic inflation, and geometry such as landslide topographic cross sections and topographic change. The mission plans for split spectrum ionospheric corrections, which will provide more accurate L-band SAR observations, which is particularly important for producing 3D vector motions by combining multiple views. In addition to providing information for earthquakes, volcanoes, and landslides, DESDynI can be used to provide estimates of carbon density for wildfire potential, and imagery of wildfires.

Unique Characteristic	Specific Return
8-day repeat	Determination of Hazard Processes Understanding of temporal scales for improved forecasting
Multiple views	3D vector measurements Feature geometry and mechanisms
Simultaneous InSAR/Lidar measurements	Combined topography and topographic change Carbon estimates for wildfire potential
Split spectrum	Ionospheric corrections for more accurate L-band observations Improved 3D vector measurements
US directed systematic measurements	Identification of active areas of interest to the US Targeted measurements after an event to understand aftershock or other probabilities

Unique Measurement	Specific Return
Radar line-of-site range change on weekly timescales	Aseismic deformation providing unique input to determination of hazard processes Understanding of temporal scales for improved forecasting
Lidar altimetry measurements	Topographic profiles Topographic change
Polarimetric SAR and multibeam lidar	Carbon estimates for wildfire potential
Decorrelation	Damage zones

1.4 DESDynI Data Products and Required Ancillary Data

Many of the DESDynI data products are similar to what are required for meeting the science objectives of the mission. Additional requirements are levied on the mission to provide georeferencing, which is important for damage assessment and response, and to shorten the latency from acquisition to dissemination of products. It is key to have standard data products that are easy to assimilate into assessment and other application tools.

UAVSAR, aircraft Lidar, and GPS data will be key ancillary data for filling in time series data and improving response times. Inventories of landslides, volcanoes, faults, cities, buildings, and estimated hazard, vulnerability, and risk will be coupled with DESDynI data to improve estimates of hazard and risk.

1.4.1 Overall Needs for all three applications

- Imagery from radar (buildings, topography) from this mission and ancillary sources; and high-resolution photography, aircraft lidar
- All data, products, ancillary and mission are planar and georeferenced,
- Atmospherically and ionospherically corrected SAR if possible (for ionosphere we do not know how to do this yet in real-time)
- Quick look SAR and InSAR products for near-real-time response need products within 24-hours of event even if not final product
- Precise real-time orbits to enable most accurate quick look products
- Map view of error; correlation matrix
- Development of standard data products (e.g. altimetry community)
- Estimates of deformation and strain from radar interferograms
- Polarimetric images following earthquakes
- Coherence and decorrelation maps following events

Required for Mission

Ground

- o Continuous GPS
- o Meteorological data; models (ionosphere and troposphere)

Attempts have been made to model the atmosphere in InSAR images based on concurrent observations [6]; however, in general any ground-based network of instruments will offer poor spatial resolution, and space based instruments [7] are typically limited to cloud-free daylight hours or by sparse repeat times. To increase the signal to noise ratio for InSAR over short temporal and spatial scales so that events can be more accurately modeled and interpreted it is necessary to adopt a more sophisticated approach to deal with the atmospheric component. The first steps in that direction used the short-term predictions from operational weather models to estimate the atmospheric delay[8-10]. The predicted delays are used to generate a synthetic interferogram that is compared with the observed interferogram and/or subtracted from it, reducing the atmospheric noise and improving the ability to identify and resolve the geodetic signals.

It would add significant value to DESDynI science and application InSAR products to extend the weather model approach and establish a weather "now-casting" system that will perform a high-resolution meteorological analysis to produce line-of-sight atmospheric delay maps for the exact time of SAR acquisitions, thereby improving the accuracy of interferograms made with 2-4 images.

It is likely too computationally expensive to assume this will be done for all interferograms created by DESDynI so clearly prioritization of sites and algorithm optimization would be necessary.

- e.g. weather analysis 1 km resolution from models

Space

- Precision Orbit Determination (onboard GPS, SLR reflector)
- Ionospheric measurement from spacecraft (e.g. split spectrum, Faraday rotation)
- Radiometer has merit for tropospheric corrections, but it not planned for the mission.

Airborne

- UAVSAR needed for applications (lower latency to supplement DESDynI and for ***calibration***

Required for Analysis and Interpretation

- Overall data organization for analysis
    - e.g. event catalog of volcano deformation; post-seismic events
    - all supporting ancillary information organized for easy rapid access for comparisons, characterization of forecasts, tracking results and decisions (and forecasts) made using products
        - GPS, Seismic, tilt, strainmeter data
        - Airborne and tripod Lidar for detailed topography and surface changes

    - Photographic imagery
    - Base GIS maps of structures, inventory
    - Thermal imagery
    - Soil Moisture
    - Geology

Earthquakes

No additional data products are needed beyond those outlined above and for meeting the science objectives.

Ancillary Data

  - Estimates of megacities inventory, vulnerability and hazard
  - UAVSAR – can be used to fill in DESDynI temporal gaps and it has potentially more rapid response
  - GPS – adds continuous data time series of deformation though sparse geographically

Volcanoes

- Radar intensity imagery: low latency (real-time) backscatter helpful if cloudy for monitoring gross changes in topography, dome growth, eruptions, explosion craters change in geomorphology, deformation

Ancillary Data

  - UAVSAR – fill in DESDynI temporal gaps and potentially more rapid response
  - Aircraft Lidar – can be used for detailed mapping of geomorphic changes due to dome growth and eruptions
  - GPS – adds continuous though sparse time series of deformation

Landslides

- Landslides have large horizontal motions so lower look angles are needed with the with radar

Ancillary Data

  - The need for lower look angles argues for UAVSAR for complimentary data.
  - Aircraft Lidar can be used to map detailed geomorphology of high-risk areas.

    - In order to fully understand landslides it is important to know the slope, soil and moisture conditions, precipitation, seismicity, and temperature

1.4.2 Specific Data and Data Products

- Raw Data (Level 0)
- Corrected data (Level 1) engineering corrections takes 2 days
    - has orbit corrections
    - could have atmospheric and ionospheric corrections
    - tide corrections
- Geocoded SAR imagery and Lidar elevation profiles (Level 2)
- Geocoded, topo-corrected interferograms and correlation maps; along track interferometry and amplitude offsets provide another component of displacement (Level 3)
- Unwrapping to get 4D surface displacements, strain, soil moisture; Lidar for ash plumes, fires.
- Models (Level 4) persistent scatterer InSAR time series

<u>Summary of data products</u>

- SAR Amplitude
- SAR Phase
- SAR Coherence
- Interferometric pairs (minimum), InSAR time series (preferable)
- Lidar elevation profiles
- Surface displacement gradients as function of time
- Surface velocities (3-D) as function of time
- Fault models
- Depth and volume of magma chamber
- Size of events
- Identification of active faults, volcanoes, and landslides

1.4.3 Derived Product Work Flow

- Standard

- On-demand processing
- Real-time quick look, low latency
- Final products
- Well developed work flow allows for quick look, reprocessing
  - high speed computing, cyber infrastructure, delivery and access

1.4.4 Data Delivery

- Get products to users with required latency, product level
  - e.g. to emergency management
  - to application and science stake holders
  - outreach and education to help users learn how to effectively use products, interpret results
  - well developed and documented workflow with errors
  - products at various levels (browse to detailed scientific applications)
- Quick look product protocols and caveats
- At least two data centers for raw data storage and for processing
  - web services; teragrid; cyber infrastructure distributed services
- Desired data and data products and required density, frequency, latency, accuracy, for science goals and objectives

1.4.5 Data Resolution etc.

- Orthogonal demands: need Radar observations to be spatially dense, often repeated; need Lidar observations to be spatially dense, but less frequently repeated for vegetation structure and biomass science objectives.
- Density: spatial resolution for Radar 20 meters - amplitude; 100 meters - phase;
- Accuracy: short and long spatial wavelength needed to be able to characterize errors in deformation rate (as good possible in time allowed for delivery and analysis) mm/year level; want accuracy and precision
- Frequency: for hazards want 4 days (or less); but want global coverage (8 days minimum for this with only one SV) could do 4 days for US only. 12 day repeats are the maximum time suitable for post-seismic studies since most signal - most of the deformation happens immediately after an event.

- Latency: ASAP but longest latency for response applications is really less than 24 hours (might require UAVSAR). Priority processing queues for various product levels, latency demands

1.5 Monitoring and Event Response Plan

1.5.1 Required Time Between Event and DESDynI Observation

Volcanoes

- Event response – large eruption – US once per decade
    - 1-day optimal for post eruption
    - Post eruption deformation extends from weeks to months
- Pre-eruption
    - could see dike injection prior to eruption with daily acquisitions
    - could aid in forecasting eruption with 8-day repeats (focus attention on all data streams for short-term prediction).
- Monitor
    - Need to do global survey of volcanoes to understand the "typical" pre-eruption signatures. 8 day repeat SAR data base for 5 years is needed with targeted LiDAR profiles desirable.
    - Need to have a person or algorithm to examine volcano data for each acquisition. Analogy to alarm algorithms for seismic and satellite thermal data.

Use Case Scenario

Volcano Event – Rainier – Major eruption …

Pre - Monitor for months and years prior to event. Detection of inflation. Need pre-acquisitions every 8 days.

Post - Seismic detection and scan InSAR archive.

1) Change background mission to optimize acquisitions until eruption ends (6 mo. To 1 yr).

2) Move data processing to top of queue.

3) Data products: amplitude within 6 hours after acquisition

phase, coherence, vector deformation < 2 days after acquisition.

End user – USGS Volcano observatory scientists begin data interpretation.

Transmission of data to end user – USGS sends data interpretation to FAA, DoD, homeland security, FEMA, and State Emergency managers.

How data product will be utilized – assess areas of impact: volcanic ash, mud flows, lava flows, volcano morphology changes, eruptive volume (event may continue hours to years).

Potential evacuation of areas, rerouting of flights, etc. based on many data types. This is based on pre-event detailed response plans. InSAR is also used with other data to assess when it is safe to go home.

Specific/quantitative gains from DESDynI data – one of many data types used to assess the risk of the volcano; may provide first indication of scale of eruptive event because it can image through ash, steam, and weather clouds.

Use Case Scenario

Seismic Event - M 6.7 event in CA

Objectives: – stress redistribution and triggered slip on nearby faults to assess potential for a large nearby earthquake as backup to other systems with faster response time.

Damage assessment from coherence (24 hours) as backup to other systems such as UAV, aircraft lidar, and other ground truth.

DESDynI Lidar: compare post-event data to before acquisition.

Raw data acquisition – retask satellite to focus on area of deformation. May need multiple swaths or scansar.

Data Processing – interferograms and stress change models.

Data Products - need interferogram to add model input into FEMA HAZUS - MH model (http://www.fema.gov/plan/prevent/hazus/hz_models.shtm).

End user – USGS and science community, Caltech,

Transmission of data to end user – USGS and California Earthquake Prediction Evaluation Council (CEPEC) evaluate all types of data and make assessments. Send to NEPC.

How data product will be utilized – to establish the likelihood of an earthquake on a nearby loaded fault

Specific/quantitative gains from DESDynI data - full deformation field.

Use Case

Landslide Event - Berkeley Hills

Pre – collect interferometric data every 8 days to build a catalog of active slides from all different SAR look angles.

Post – quickly examine catalog for size and shape of moving slides in the region. This is used to deploy ground systems.

Reprogram DESDynI to collect data every 8 days for 3-6 months following event. Also assess nearby slides for activity.

…

Data Processing – SAR amplitude offsets for large displacement measurements, interferograms and coherence for post slide motion.

Data Products – Amplitude image; InSAR

End user – California Geological Survey, Emergency Services, and USGS.

Transmission of data to end user -

How data product will be utilized – deploy ground instruments and measure post motions

Specific/quantitative gains from DESDynI data – full 3-D spatial deformation field and use of catalog of active slides.

1.6 Targets and Observational Frequency

Earthquakes, volcanoes, and to some extend landslides are all associated with and occur most frequently within actively deforming regions (Figure 6). Landslides occur where there are slopes, and large earthquakes can occur in intracontinental regions. Therefore, the rapidly deforming regions should be observed frequently on weekly timescales, but a baseline set of observations should at minimum be collected for all of the landmasses at the beginning and end of the mission. Yearly to sub-yearly measurements for the intracontinental regions would be better if the observing scenarios allow.

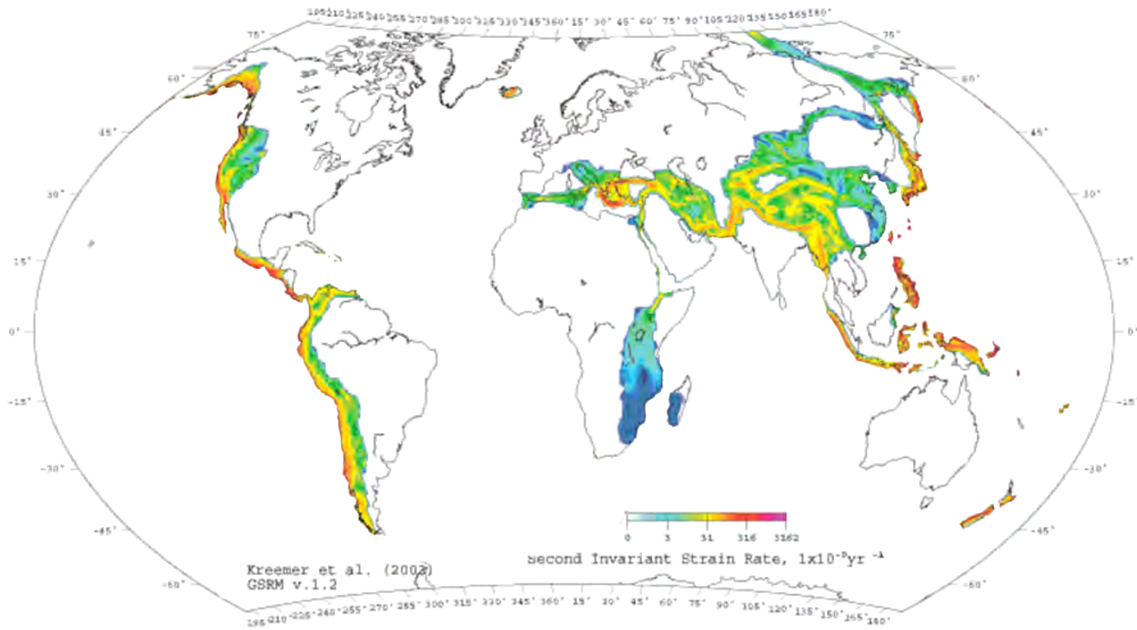

Figure 6. Strain map showing rapidly deforming regions [11].

2. Hydrological and Ocean Applications

The Integrated Global Observing Strategy (IGOS), Oceans Theme [12] and Coastal Theme [13] Reports have identified the need to improve observations of the oceans and coastal regions, from oceans-to-land and land-to-oceans, for societal benefits that include disasters, health, energy, climate, water, weather, ecosystem, agriculture, and biodiversity. NASA is interested in coastal ocean regions that specifically relate to understanding how the climate is changing and how those changes impact life. DESDynI will provide key information on coastal circulation, waves, and wind needed to improve observations and understanding of wetlands, coastal hazards, coastal management, oceanic components of the hydrological and biogeochemical cycles, and ecosystem health and productivity.

Systematic, frequent, and all weather polarimetric SAR data and coupled Lidar observations provided by DESDynI will advance emergency response and promote ecological relevancy and broaden the user base of derived products. SAR mapping capabilities provide information that can be used by emergency response personnel to assess disasters such as flood extent or levee failure, particularly when clouds obscure optical image data collection. Similarly, unimpeded by weather constraints, ecological indicator trends based on systematic spatial and temporal sampling intervals and a high frequency Lidar data coverage will provide unique measures of ecosystem health and function. The nearly continuous information availability at regular intervals will allow coastal resource managers, policy makers, and emergency response agencies to fully incorporate remote mapping products into their management plans, regulatory structure, and rapid reaction preparations.

2.1 Applications in the Context of DESDynI

DESDynI will play a significant role in mapping and monitoring floods, oceans, and coastal regions, including wetland ecosystems, disaster, health, energy, climate, water, weather, agriculture, and biodiversity at local to global scales. The need to map these areas includes detection and monitoring of invasive species, flooding extent, wetland quality, water quantity, wildlife habitat, and carbon storage credit accounting. There have been significant demonstrations of L-band and other wavelength SAR data for a variety applications related to hydrological impacts including those on carbon storage. DESDynI will be a key component for providing radar and lidar data to understand local and global wetland infrastructure in light of climate change pressures. NOAA has used SAR extensively as an observational tool [14] for monitoring coastal weather effects (i.e., safety of life and property), ecosystem health, fisheries management, and hazards, and for any associated response.

In combination with satellite and aircraft optical imagery, DESDynI data and derived products will significantly improve consistency of landcover monitoring as well relevancy of the information to ecological studies and resource management. The canopy structure monitoring capability available with polarimetric SAR and Lidar instruments can provide much improved biophysical information such as biomass, orientation, and height, and landcover classifications. SAR polarimetric data can be used to monitor wetland regrowth if regrowth is accompanied by a preferential change in canopy leaf orientation [8]. Overstory canopy structure related to gaps and understory establishment and growth are active topics of ecological research. Enhanced information will promote the understanding of vegetation response to changing forcing factors such as climate, storm frequency, and management practices. In turn, responses of the coastal ecosystems can be anticipated, mitigation approaches enacted, and management practices adapted before detrimental changes become inevitable.

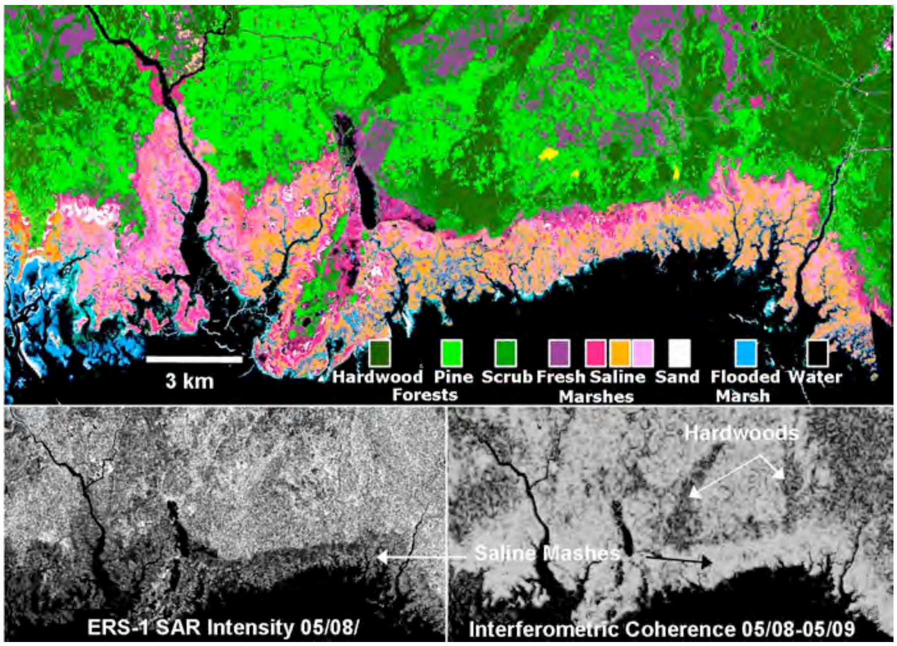

Figure 7. (top) Coastal landcover classification based on combined optical and SAR image data covering the U.S. Fish and Wildlife St. Marks National Wildlife Refuge in the Florida Panhandle. Higher classification detail was produced with the integrated dataset (e.g., multiple marsh structures were identified in the single species saline marsh). (bottom) A coherence image created from ERS-1 and ERS-2 (intensity image not shown) SAR image collections separated by one day. Hardwood forests are clearly distinguishable on coherence image but not on the intensity images[15].

SAR image data coupled with pre-existing landcover classifications can provide coastal resource change detection when optical image data is unavailable (e.g., clouds, haze, smoke, extreme illumination variability). Further, interferometric SAR (InSAR) coherence maps, generated from DESDynI data, can discriminate between coastal landcovers often indistinguishable with SAR intensity data or optical data (Figure 7)[15]. In studies where optical and SAR data have been combined, landcover classification detail was improved.

Ability to detect subtle changes in the coastal landscape condition is particularly suited to coupled polarimetric SAR and Lidar capabilities offered by DESDynI. Polarimetric SAR and particularly full waveform Lidar data could provide detailed canopy structure information improving detection of abnormal changes. This enhanced landscape condition mapping coupled with frequent DESDynI observations will help advance monitoring of ecosystem status and health from one based on opportunistic observations to understanding and discovery based on a systematic and temporally consistent ecosystem data [16].

2.1.1 Wetlands

The difficulty of mapping wetlands on the ground, the limited ability of optical data to map forested wetlands, and the demonstrated suitability of SAR for wetland mapping have increasingly led those responsible for informing wetland management decisions to more fully explore and/or use SAR data to map and monitor wetlands - particularly forested wetlands. For example, the United States Department of Agriculture (USDA) Conservation Effects Assessment Project (CEAP) is tasked with the evaluation and enhancement of conservation practices used to improve environmental health by reducing the impact of agriculture on aquatic ecosystems and other natural resources. One focus of CEAP, is to evaluate the effectiveness of wetland conservation practices (e.g., wetland construction, wetland restoration, and other types of wetland enhancement) for improving the delivery of wetland ecosystem services. The CEAP-Wetlands study is currently developing a tool based on SAR as well as other geospatial data and ground measurements to improve the mapping of forested wetlands and to monitor wetland hydroperiod – a key driver of wetland ecosystem services. The tool will be used to target and prioritize wetland management actions, monitor wetland condition, and estimate the provision of ecosystem services across the landscape. In projects funded by the US Department of Transportation and State Departments of Transportation, SAR is being used to detect forested wetlands because they are the most difficult to map using traditional remote sensing methods and they need to be avoided for new road construction. In a recent report of the Great Lakes Coastal Wetlands Consortium (GLCWC) to the EPA, GLCWC determined that new technologies, and in particular Synthetic Aperture Radar (SAR), are required for effectively monitoring the coastal Great Lakes Basin. The potential of SAR data is currently being investigated by multiple federal agencies and other groups as a way of providing information to environmental decision makers. The use of SAR data to meet the operational needs of federal agencies and other groups is becoming increasingly possible as the availability of SAR data increases; however the availability of L-band data is still limited. DESDynI could help fill this data gap.

Coastal Wetlands

The latest 2008 IPCC report: "Water and Climate Change" addresses the significance of wetlands and states "Due, in part, to their limited capacity for adaptation, wetlands are considered to be among the ecosystems most vulnerable to climate change" (http://www.ipcc.ch/ipccreports/tp-climate-change-water.htm). At local to regional scale, wetlands are a vital link in hydrologic systems serving major ecological roles in the health of watersheds. Wetlands serve many important ecosystem functions such as flood storage, pollutant reduction and habitat for fish and wildlife. At the global scale, wetlands act as major sinks for important atmospheric greenhouse gases and have enormous capacity to store carbon (Dr. Ed Nater, University of Minnesota, written communication). Therefore wetlands have the potential to regulate greenhouse gases that can contribute to climate change. However, wetlands are at risk due to anthropogenic influences and are highly susceptible to changes in weather factors such as temperature and precipitation and sea level rise brought on by a changing climate.

The importance of wetlands in regards to climate change cannot be understated – both in regards to their potential as a mitigating force and their vulnerability. Despite their importance in the carbon cycle and their marked vulnerability to climate change, the locations, types, and extents of wetlands around the world are not well known. The weakest element of water and ecosystem research and management systems is the reliance on old, incomplete, and static landscape-scale data that are inconsistent, particularly across political boundaries. Effective assessment of ecosystem health, climate change and wetland management requires a consistent monitoring and mapping capability for routine updates. Furthermore, improved understanding of wetland hydroperiod such as temporal fluctuations in inundation and soil saturation, which is the most important abiotic control on wetland extent and function and would provide insight into how wetlands deliver ecosystem services, such as carbon sequestration. This knowledge would guide what can be done to enhance the provision of these services. Although the mapping and monitoring of wetlands has historically been challenging, the increased availability of SAR data and the development of new SAR processing techniques has led to significant progress. SAR is unique in that it can collect imagery regardless of weather and solar illumination to provide information on vegetation structure, extent of flooding, and depth of flooding in wetland ecosystems, even when the ground's surface is obscured by vegetation. These capabilities allow not only the mapping of wetland type, but also the mapping of hydrologic condition year-round, and detection of important or problematic plant species such as the invasive species *Phragmites*.

The Great Lakes Coastal Wetland Consortium (GLCWC) requires mapping and monitoring and mandates developing a monitoring plan for assessment of the health of the Great Lakes Ecosystem. The GLCWC sponsored pilot projects with funding from the EPA for remote sensing technique development and demonstration of current technologies and sensors. The Consortium found one of the most promising results to be those which used a fusion of multi-date, multi-sensor C- and L-band satellite data with Landsat images. Using the fused data, maps of wetland type and extent and adjacent stressors such as agriculture, high versus low intensity urban areas, and the invasive species *Phragmites australis* were developed [17-19]. These maps had 94% accuracy when compared to the NWI maps, but they further delineated emergent species into finer classes such as Typha spp. and the invasive *Phragmites*. Phragmites form impenetrable stands with thick detritus that virtually eliminate ecological function for vast areas of highly productive coastal wetlands. It is this structure that allows it to be differentiated from other herbaceous wetland types in SAR imagery. These aggressive invasive plants have drastically reduced biodiversity and ecosystem function affecting fish and wildlife. The predicted drop in Great Lakes water levels due to global climate change is anticipated to increase the spread of non-native species in the Great Lakes coastal zone. No maps of the extent of infestation currently exist, and SAR represents a unique tool to effectively map this invasive species. More recent research, funded by the USFWS, is being conducted to evaluate the capability of the new L-band PALSAR sensor for mapping the extent of this invasion on Lake St. Clair. The preliminary maps were tied to field observations with high correlation using the single polarization and dual polarization modes. Fully polarimetric data have not been collected except in limited areas. While multi-date L-HH, L-HV data have been found to be effective for distinguishing Typha from Phragmites, fully polarimetric data are expected to increase the capability to effectively monitor a wider range of species, including endangered and exotic species.

Boreal Wetlands

The potential of DESDynI for northern ecosystems is demonstrated by results of a joint University of Michigan and JPL research project. Two seasons of PALSAR L-band imagery were used to produce a thematic map of wetlands throughout Alaska. The classification is developed using the Random Forests decision tree algorithm (Ho) with training and testing data compiled from the U.S. Fish and Wildlife Service, National Wetlands Inventory (NWI) and the Alaska Geospatial Data Clearinghouse (AGDC). Mosaics of summer and winter JERS-1 L-Band SAR imagery were employed together with other inputs and ancillary data sets, including the SAR backscatter texture map, slope and elevation maps from a digital elevation model (DEM), an open water map, a map of proximity to water, data collection dates, and geographic latitude. The accuracy of the resulting thematic map was quantified using extensive ground reference data. This approach distinguished as many as nine different wetland classes, which were aggregated into four vegetated wetland classes. The per-class average error rate for aggregate wetlands classes ranged between 5% and 30.5%, and the total aggregate accuracy calculated based on all classified pixels was 89.5%. As the first high-resolution large-scale synoptic wetlands map of Alaska, this product provides an initial basis for improved characterization of land-atmosphere CH_4 and CO_2 fluxes and climate change impacts associated with thawing soils and changes in extent and drying of wetland ecosystems. DESDynI would make such mapping and monitoring possible for boreal environments.

2.1.2 Coastal Flooding

The rapid and direct detection and monitoring of coastal flooding extent can serve to minimize loss of lives and property and help direct response and recovery efforts. Long-term detection and monitoring of marsh and wetland forest flood frequency and extent provides direct and synoptic regional observations of marsh and wetland forest status and trends, particularly the temporal and spatial variation in flood extent, duration, and depth. Monitoring coastal flooding and ecosystem status and trends share many objectives and therefore require similar data products.

While flood extent mapping has been documented in marsh and forested wetland landscapes, sub-canopy flood detection is still an active area of research [20, 21]. For forested wetlands InSAR has been used to measure changing water levels, leading to predicted flood water depths. (Figure 8) [21]. DESDynI L-band SAR will provide improved two-way canopy penetration as compared to existing C-band sensors, particularly important for leaf-on wetland forest conditions. Though more work is needed to refine water level mapping in marshes and to provide detection thresholds, the long-term InSAR coherence has been documented in marshes, indicating ability to produce water level change maps (Figure 7).

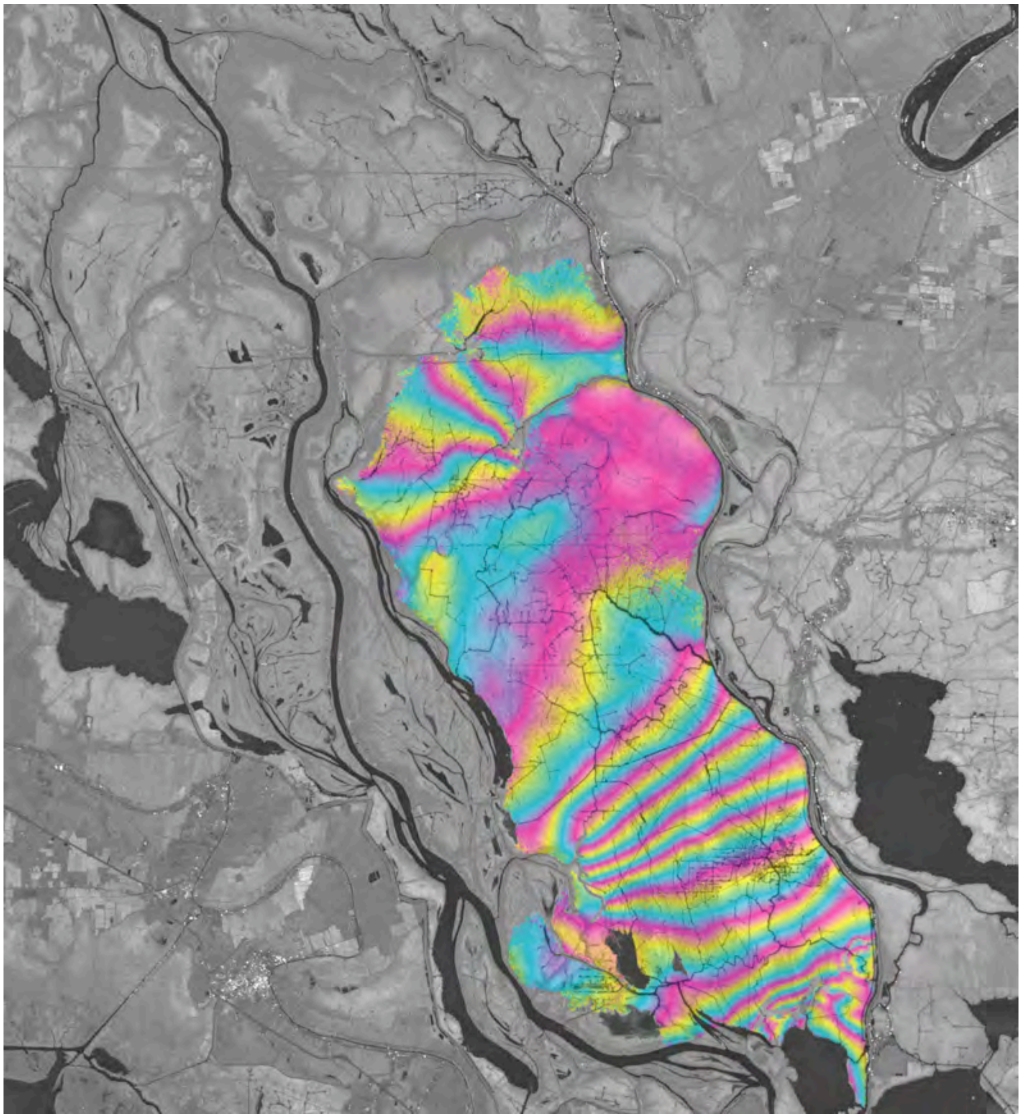

Figure 8. An InSAR image from the C-band (wavelength of 5.7 cm) Canadian Radarsat-1 satellite, capturing the dynamic water-level changes over a portion of swamp forest at the Atchafalaya basin over southeastern Louisiana[22]. The InSAR image was constructed from two radar images acquired on May 22 and June 15, 2003. Each fringe (full color cycle) represents a 3.1-cm change in water-level. The total water-level change was more than 30 cm over the imaged water basin. The image width is about 53.3 km.

2.1.3 Forest Hydroperiod

SAR data have the potential to improve the capability of monitoring forested wetland hydrology. Forested wetland hydroperiod is difficult to monitor at a watershed scale using ground-based and optical remote sensing methods alone. Multi-temporal C-band SAR data (C-HH and C-VV), collected by ERS-2 and ENVISAT satellite systems, were compared with field observations of hydrology (i.e., inundation and soil moisture) and

National Wetland Inventory maps (U.S. Fish and Wildlife Service) of a large forested wetland complex in the Chesapeake Bay Watershed [23, 24]. Significant positive, linear correlations were found between the both radar signal and percent area flooded and soil moisture. The correlation (r^2) between the multi-temporal radar signal and average soil moisture was 0.88 (p = <.0001) during the leaf-off season and 0.87 (p = <.0001) during the leaf-on season, while the correlation between multi-temporal radar signal and average percent area inundated was 0.82 (p = <.0001) and 0.47 (p = .0016) during the leaf-off and leaf-on seasons, respectively. When compared to field data, forested wetland maps created using the multi-temporal radar data identified areas that were flooded for 25% of the time with 63-96% agreement and areas flooded for 5% of the time with 44-89% agreement, depending on polarization and time of year. The increased ability of L-band SAR data to penetrate the forest canopy should lead to improved correlations with inundation and soil moisture. The results indicate that SAR data can be used to monitor wetland hydrology and that this information is valuable for wetland mapping. Improved forested wetland maps and the ability to monitor wetland hydroperiod is an important first step towards quantifying the provision of wetland ecosystem services, including carbon sequestration and pollutant removal, at the landscape scale. Furthermore, the ability to quantify wetland hydrology at the landscape scale and the hydrologic connections between wetlands and adjacent water bodies will inform the wetland regulatory debate currently ongoing within the federal government.

2.1.4 Ocean and Coastal Waters

DESDynI could make a substantial impact on safety of life and property in the oceanic coastal zone by providing timely information on winds, waves, slicks, vessels, and boundary layer meteorological phenomena. DESDynI can make unique contributions by providing improved temporal and spatial sampling, such as by providing rapid observation retasking to cover hazards such as oil spills, and by providing L-band high-wind measurements in severe storms and hurricanes which may provide superior accuracy to that available from C- and X-band SAR satellites. Wind speed maps provide detailed information on local and regional scales that are useful for identifying coastally induced wind variations such as gap winds and barrier jets, properties of Langmuir circulation and roll vortices, and the impact of wind on the transport and dispersal of spills and freshwater plumes.

Maps of eddies, fronts, and ocean surface radial velocities provide information on the temporal and spatial variability of coastal circulation, the scales and locations of these features and possible generation mechanisms. Eddies and fronts play important roles for recruitment and survival rates of many types of larval and juvenile fish species. Adult fish of many species are known to congregate along convergent zones and fronts in search of food and thus such information can be used to improve the understanding of the physical environment for fisheries management purposes. Eddies and fronts have the potential for vertical pumping of colder, nutrient-rich water to the surface. Assessments of the transport and dispersal of stormwater discharge, seeps and spills can be determined as potential coastal beach and ecosystem hazards (Figure 12 Figure 13) or even as additional nutrient sources that may impact productivity, including possibly the development of harmful algal blooms.

The coastal oceans defined as within a few hundred kilometers of land are physically complex, are often the most productive regions of the global oceans, are often adjacent to the largest concentration of human populations and hence include the most significant levels of human ocean activities. The impacts from large storms, climatic conditions such as El Nino, the Pacific Decadal Oscillation, and sea level rise, and both natural and anthropogenic forms of pollution hazards will be greatest here, both on the human condition and the biological productivity and health of the ecosystems.

Imaging radar has been extensively demonstrated to provide fine resolution observations of the ocean surface including surface wind speed and direction (including for hurricanes and other severe storms) (**Figure 9** and Figure 10), ocean circulation features including current shear boundaries, eddies (Figure 11), and temperature fronts including upwelling, ocean swell height, direction, wavelength, and wave spectra, internal waves, and ocean surface radial velocities [14, 22]. The imaging of these features results from a unique combination of surface roughness, short and long wave interactions, wave and current interactions, and the Doppler motion arising from the ocean moving during the imaging process [25]. In addition to winds, atmospheric features and boundary layer interactions are also observed by SAR through surface variations of backscatter produced by the mesoscale atmospheric condition or local wind conditions. These include roll vortices, cellular convection, lee waves, barrier jets, and gravity waves [5]. SAR can uniquely detect slicks from both natural and anthropogenic sources including natural seeps, oil spills from ships and platforms (Figure 12), stormwater and river plumes (Figure 13), wastewater discharge, and biogenic slicks arising from ocean productivity (Figure 11) [15]. Combining these fine resolution and all-condition observations with other primary sources of ocean sensor data from satellites, aircraft, and in situ platforms including sea surface temperature, ocean color, vector winds, and sea surface height can provide an unprecedented detailed view of the coastal oceans.

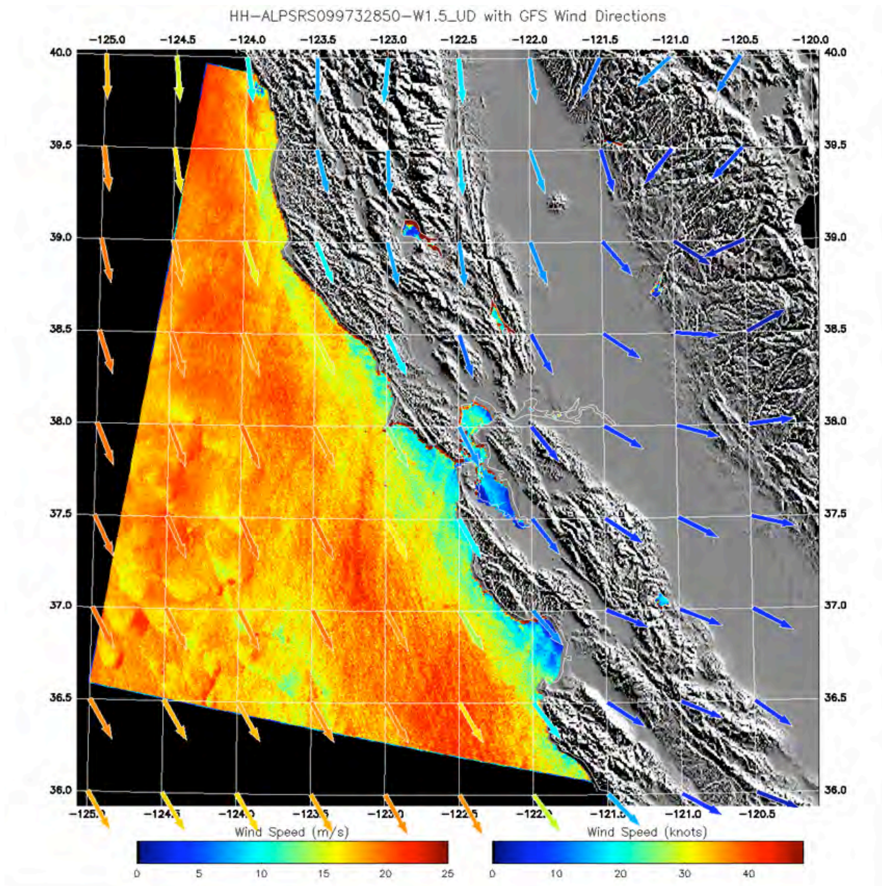

Figure 9. L-band SAR wind image derived from ALOS PALSAR data. The arrows are the NOAA Global Forecast System (GFS) model winds used to provide wind direction information. The wind speed color table for the model wind arrows is the same as is used in the SAR wind image. Note that winds are also calculated in lakes and bays and right up to the shore.

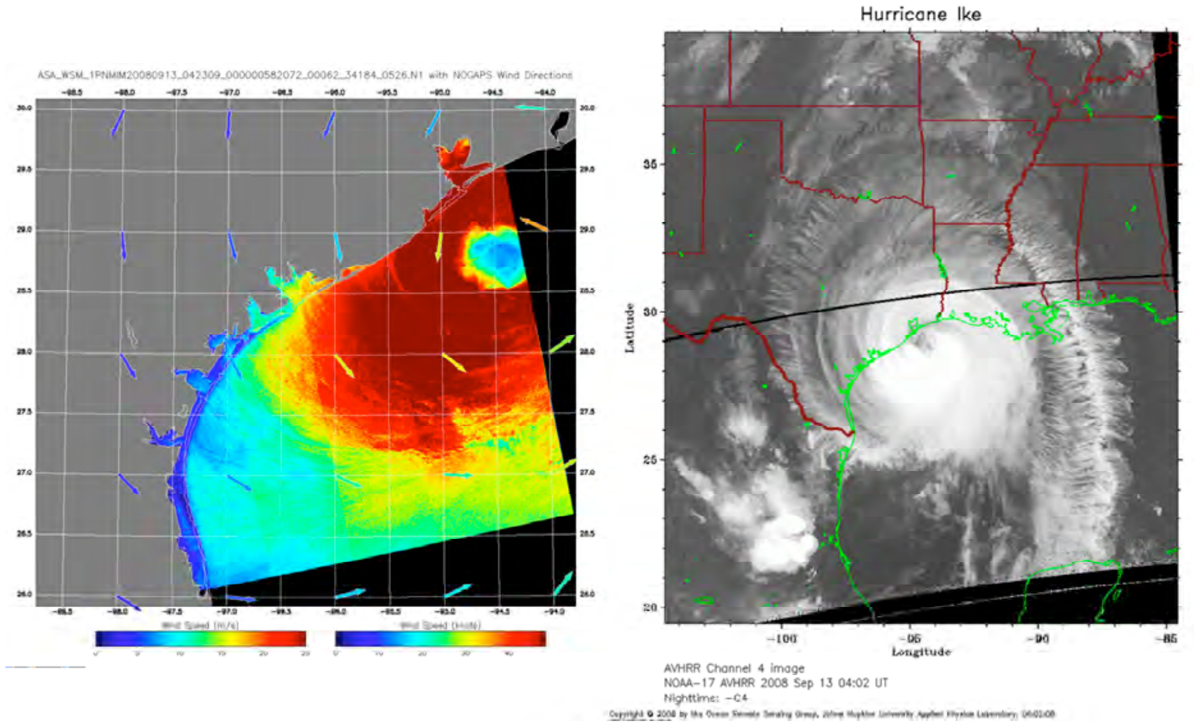

Figure 10. Hurricane Ike. Left – ENVISAT Advanced SAR wind speed image, 09/13/2008 04:23 UT, just before landfall at Galveston. Right – NOAA-17 AVHRR Channel 4 (Thermal IR) channel image of Ike 09/13/2008 04:02 UT.

Although each of these measurements or detection/monitoring capabilities have their own limitations, they offer the advantage that most can be achieved solely through the use of imagery. However, marine wind speed does depend on accurately calibrated Normalized Radar Cross Section (NRCS). Doppler-derived ocean surface radial velocities make use of phase information included within single-look complex data [25]. Phase information can also be employed in determining wind and wave direction. Although many of the these applications have matured using the widely available C-band imagery from Radarsat-1, ERS-1/2, and Envisat, the original work with Seasat followed by SIR-B, SIR-C, and JERS-1 and the more recent work with L-band ALOS PALSAR confirm that these same applications are possible and even improved at this frequency.

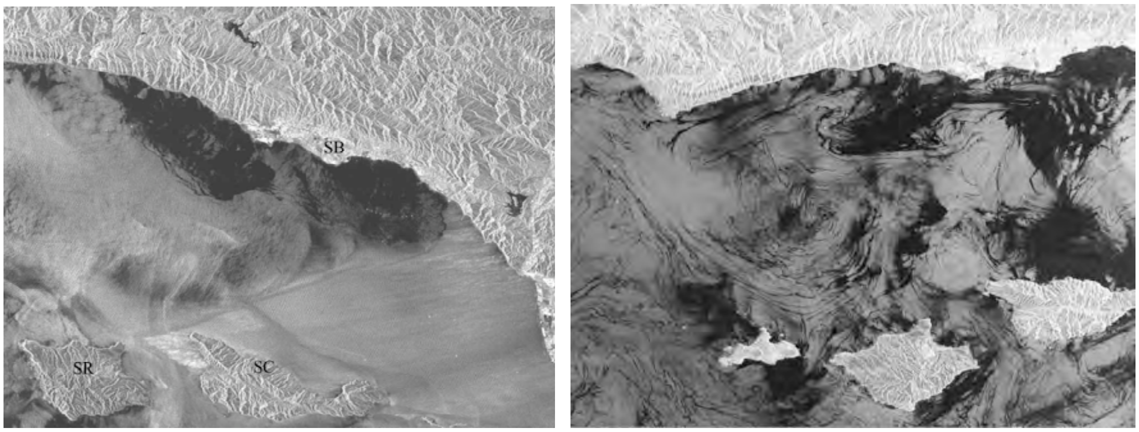

Figure 11. This pair of Radarsat images were obtained in the Santa Barbara Channel on January 8, 2003 at (top) 02 GMT and (bottom) 14 GMT. The top image shows westerly swell, strong offshore winds in the east extending out to the western tip of Santa Cruz (SC) Island, two calm (dark) zones adjacent to Santa Barbara (SB) indicative of lower winds plus the presence of natural oil seeps and perhaps surfactants from the nearshore kelp beds. Twelve hours later, during the local morning, the winds are calmer. A large cyclonic eddy in mid-channel plus several smaller cyclonic eddies are revealed, primarily through the presence of surfactants being swept along by the eddy rotational currents and forming curvilinear narrow streaks. A jet-like flow pattern is also indicated between Santa Cruz and Santa Rosa (SR) Islands. Several ships and associated stern wakes are also shown, including a long ship wake that has been rotated by the large eddy. The two calm zones near Santa Barbara have basically persisted with additional calm zones present in the lees of the islands.

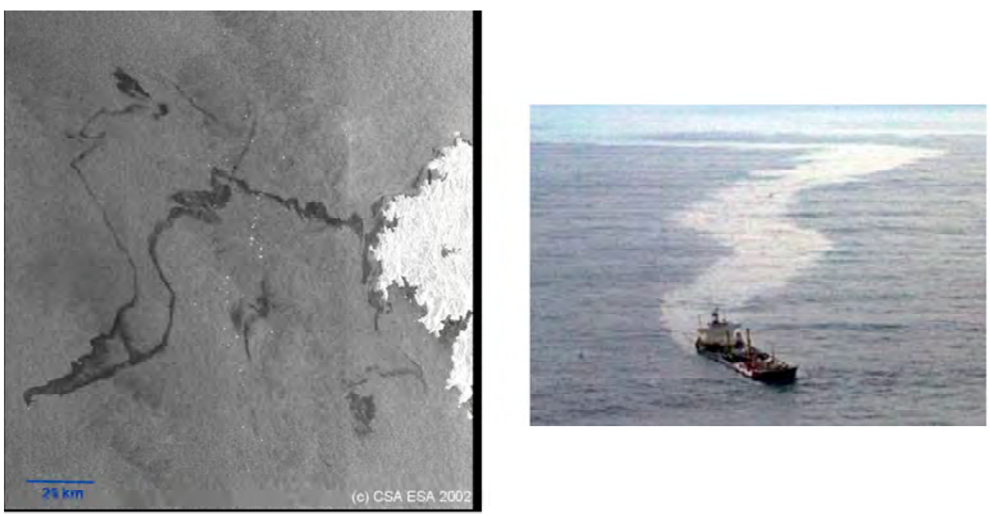

Figure 12. Prestige oil spill, La Coruña, Spain. (left) ENVISAT ASAR Wide Swath, 17 November 2002 10:45 UTC showing oil spilled from drifting ship (ship is located at end of dark trail, lower left side of image). (right) AP photo of Prestige spilling oil west of Spain, November 14, 2002.

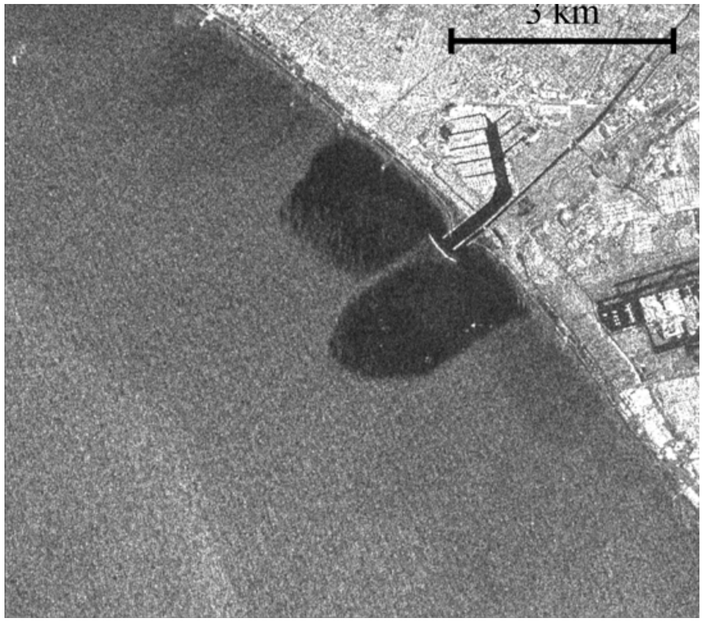

Figure 13. Radarsat image of Los Angeles area of stormwater discharge plumes exiting Ballona Creek after a rain event, obtained November 8, 1998. Ballona Creek is just south of Marina del Rey, a small boat harbor in Santa Monica. (DiGiacomo et al., 2004).

2.1.5 Ice and Navigation

SAR has been found to be an extremely valuable sensor for observing many conditions and parameters of ice, including sea and lake ice type, age, concentration, extent, motion; iceberg detection and tracking; river ice; glacier and ice sheet extent and velocity fields. The all-weather and fine resolution capabilities of SAR have proven very useful for navigation and ice mapping applications as well. For example, SAR imagery is valuable for analyzing ice conditions in the Great Lakes, sea ice in all ice-covered seas, and river ice (particularly during spring break-up). These applications are important for improving shipping, navigation and safety of coastal communities and coastal fishing and hunting activities. Experience with previous L-band radar data indicates L-band imagery from DESDynI may actually be superior to C-band imagery for ice classification, particularly with its multi-polarization capability. Radar observations of ice are becoming more important as the climate of the Arctic and Antarctic is undergoing significant change, particularly sea ice extent and thickness distribution and ice sheet retreat. The Arctic ice changes appear to be having significant impact on marine mammals as the environment shifts towards subarctic ecosystems. Also L-band data appears to improve sea ice type and motion measurements as well as ice sheet velocity estimates [26, 27]. It is critical to capitalize on DESDynI to continue these observations for climate observations as well as navigation.

2.2 Goals, Objectives, and Observation Needs

The primary goal for hydrological and ocean applications is to *minimize hazards and understand the impacts on ecosystems, habitability, and navigation from floods, coastal oceans, and sea and lake ice cover*. The objective is to *characterize the status and trends of floods, coastal oceans, and ice*. DESDynI SAR imagery and products will improve the observations of the oceans and coastal waters, wetlands and coastal regions, and sea ice leading to improved understanding and monitoring for minimizing impacts. The DESDynI L-band frequency in both standard and wide swath modes, the capability for multipolarization channels, the InSAR capability, the ability to image on either side of the satellite track and for retargeting, and the availability of repeat coverage over a few day interval will significantly increase our understanding and monitoring potential of the coastal regions, oceans and ice for climate and hazards.

Systematic satellite observations with timely data delivery will improve the understanding of the coastal ocean circulation and resources in the coastal environment and improves the monitoring, preparedness, and response to coastally-related emergencies that arise from disasters, such as flooding, storms, and oil spills. This will advance linkages between casual forces and coastal resource and ocean dynamics and responses. This understanding will help to minimize hazards, promote timely environmental response and ecological relevancy, elevate status and trends monitoring of floods, coastal oceans, and ice, enhance emergency response performance that serves to protect life and property, advance management of coastal and ocean resources, and broaden the user base of the derived products.

There is now a long history stretching back to Seasat of applying satellite SAR data to research questions and practical applications in hydrology, oceanography, and coastal ecosystems [27, 28]. Seasat carried an L-band SAR and thus early satellite SAR research focused on L-band SAR data. Since then, most of the research has been accomplished with available C-band SAR data. Thus, re-invigorated research and development is warranted with L-band data, as well as multi-frequency, and multi-polarization SAR data. None-the-less, past experience with Seasat, the Shuttle Imaging Radar SIR-B and SIR-C missions, and recent experience with Advanced Land Observing Satellite (ALOS) Phased-array L-band SAR (PALSAR) data provide full confidence that DESDynI SAR data will have great utility for hydrological and ocean applications.

2.2.1 Ocean and Sea Ice

For most open ocean and ice observations, ScanSAR data is preferred (swath widths over 300 km). Standard strip mode imagery (swath width ~100 km) is needed for many coastal, river, and lake applications and open ocean applications requiring higher resolution. Unfortunately there is no one single SAR observing mode that is best for all ocean applications. Applications such as waves, icebergs and detection of small vessels, river ice, oil platform detection, oil spills, and surf conditions all require high-resolution data (25 m resolution, 120 km swath). For ocean hazard events such as oil spills, and oil-platform change detection even higher resolution are required (3-10 m resolution with 25-50 km swath). However, for ice motion applications, wind speed, and detection of large vessels in the open ocean, ScanSAR (100 m resolution, 300 km swath) is perhaps most valuable. Ridged ice is best observed with finer resolutions, on the order of 5-10 m. In general, the lower range of incidence angles (15-35 degrees) are preferred for ocean imaging, as the higher range of angles may fall closer to the noise floor under lower wind conditions. Imaging of ice is satisfactory over a broad range of incidence angles. Although ocean and sea ice applications have preferred modes of operation, it is important to note that useful data can be made in virtually any imaging mode.

Accordingly, some effort should be expended to define and prioritize observational requirements to make most efficient use of DESDynI data. However, the following needs are clear.

River and lake ice data acquisitions will normally be embedded in land data takes. Coastal ocean and sea ice applications can in many cases be achieved by simply extending land applications data takes by a minute or two. More offshore coverage for ice and winds will require dedicated passes. Although it is unrealistic to cover large expanses of open ocean, coverage of ice-covered ocean areas and near-coastal ocean areas for which weather and conditions can impact population centers and coastal activities is desirable. In general, ocean applications have particular value in the Exclusive Economic Zone of the United Stares (200 nautical miles or 370 km) from the shore. The types of ocean and atmospheric features and pollution hazards that are best detected by SAR have generally relatively short time scales and require repeat imaging on the order of 0.5-3 days. Many coastal studies may be seasonal in nature or short-term based on events or field experiments. Another consideration for coverage is in terms of night or day, as many coastal regions are characterized by diurnal winds, which are often seasonal as well. Diurnal winds generally indicate calm winds in the early morning hours and higher winds in the afternoon and evening. This results in the desire for twice-per-day imaging when possible (Figure 11).

Ocean observations generally prefer HH polarization, but can use any like polarization for geophysical measurements. There is one exception: we expect that VV polarization would provide better wind vector measurements, though HH can still work. Vessel and platform detection improve with cross-polarization imagery.

2.2.2 Coastal Resources

In order to incorporate the on-demand necessities of emergency response and the systematic and continuous needs of coastal monitoring, a variety of mapping spatial and temporal scales are desirable. Pre-event data acquisition strategies that incorporate DESDynI observation opportunities should be developed. SAR collections covering large regions (e.g., 300 km swath) offer moderate spatial resolutions (e.g., 100 m or less) and the ability to capture threatened pre-event and emergency response post-event impact areas at weekly to daily repeat frequencies are desirable. Pre-event coastal landscape condition and open water spatial distribution provide a baseline for quick evaluation of landscape change and flood extent and water depth changes. Large-format modes also provide synoptic captures that allow regional perspectives of coastal wetland and adjacent upland condition, phenology, and soil moisture content, and most often provide the first evidence of change. While large-format SAR collections will provide regional and pre-event detection, moderate swath (e.g., 60 km) and higher spatial resolution (e.g., 25 m) modes afford canopy stand-level information necessary for (a) determining the underlying coastal wetland function, (b) canopy structures (e.g., canopy gaps, subcanopy size and species type distributions), and (c) regeneration and shifts in coastal wetland species associations in response to storms, flooding, herbivory, fires, and climate changes. In addition, these higher resolution SAR modes are most compatible with and complementary to the Lidar data collections that offer enhanced canopy structure information. Accordingly, pre event planning is required to determine the optimum DESDynI data acquisition strategy.

2.3 Data Products, and Required Ancillary Data

2.3.1 Data Structure Availability

In addition to a systematic and continuous data stream for monitoring and emergency response, the collected image data and derived products should be directly relevant to ecologic status and health and coastal management responsibilities. Most important is that the data and derived products be immediately useable to coastal researchers, resource managers, policy makers, and the emergency response personnel. Accordingly, all polarimetric DESDynI SAR image data should be available as (1) Level-0 and higher, (2) Single Look Complex (SLC), (3) calibrated, and (4) georeferenced. In addition, interferogram and coherence maps from adjacent epochs should be produced at the distribution centers and available to the user. Full waveform data Lidar data should be available to the user.

2.3.2 Coastal Resource Monitoring

The integration of optical and SAR image data collections will fundamentally change the mapping and monitoring of coastal ecosystems [29]. (1) DESDynI polarimetric SAR, InSAR, and Lidar data and derived canopy structure products in combination with optical image data and ground-based occupations will improve understanding of how and why vegetation shifts in response to variations in climate, flushing strength, and management activities (e.g., controlled burns, silviculture, water controls). Examples include the establishment and spread of invasive species and the shifts in wetland forest and marsh communities with changing temperature extremes and sensitivities to storm wind damage. (2) Incorporating SAR image data into landcover classification strategies will improve both the landcover detail (number of class types) available and the landcover repeat frequency (Figure 7). (3) DESDynI data in combination with optical data and products will advance the detection of subtle and adverse changes in the coastal resource, thereby, enhancing the monitoring of ecosystem status and health and the potential to mitigate before irreversible change has occurred. (4) Including SAR and InSAR mapping capabilities into optical biophysical coastal resource mapping will better link ecosystem status and health indicators (e.g., biomass, canopy structure) with function (e.g., regeneration, recovery) and driving forces (e.g., silviculture, fires, storms, flooding). With these complementary optical datasets, 90% to 100% of the coastal monitoring products can be successfully produced while anticipated success is 40% to 50% without this optical information.

2.3.3 Coastal Flooding

The following are needed to minimize impacts from coastal flooding: (1) Improved landcover and canopy structure information (via polarimetric SAR and Lidar) integrated with historic and event driven extent and staging information should provide better estimates of the frictional component of storm surge for flood models. (2) Improved frictional estimates and concurrent hydrological and meteorological data combined with DESDynI products such as updated soil moisture and digital elevation maps should improve flood vulnerability prediction and provide the capability for continuous reassessment. (3) Adding infrastructure and population distribution information allows extending these at risk simulations to human populations and facilities. (4) Important for protection of human lives and properties, DESDynI provides the possibility for more timely and accurate construction of shoreline location maps. With these complementary datasets (e.g., staging information, meteorological) 90% to 100% of the outlined flood products should be successfully produced while without this complementary information, anticipated success is 50% to 60%.

2.3.4 Coastal Oceans and Ice

For coastal and sea ice applications, we can effectively use Level-0 data, SLC data, calibrated, geo-referenced backscatter (and polarimetric) data, for coastal winds and sea ice motion and waveform lidar for sea ice thickness. If these data are provided, it may be the case that other government or academic institutions could routinely create data products appropriate for coastal applications. However, some of the applications have progressed sufficiently that NOAA, and perhaps the DESDynI project, may select to routinely produce the following data products: wind speed and direction, wave height variance spectra, vessel and platform locations, surfactant/oil spill/oil seep maps, Doppler-derived ocean surface current radial velocity maps, sea/lake/ river ice analyses, and iceberg locations with alerts.

Coastal ocean applications can achieve from 80 to 90% of their maximum potential solely with DESDynI SAR data. Optical imagery from airborne or satellite platforms can aid in vessel detection, platform location, ice and iceberg location and classification. Optical imagery can also help verify natural seep locations observed in SAR imagery. Buoy data and wind and wave forecast models can provide continuing validation and the ability to interpret wind and wave measurements in the appropriate context. Known platform locations can act as fiduciary data in determining vessel and platform locations. Sea surface temperature, ocean color measurements and salinity satellite data (Aquarius) should help confirm that features in SAR imagery are coincident with circulation features and different water masses. With these additional data the coastal ocean applications potential would reach 90 to 100% of what we can expect.

Air temperature data and SST imagery can aid in the interpretation of ice imagery. However, we expect 90 to 95% of the potential quality of the measurements can be achieved with no ancillary data; improving to 95 to 100% with these data.

2.4 Monitoring and Event Response Plans

2.4.1 Systematic Monitoring

Detecting and quantifying changing trends (monitoring) and dramatic change (e.g., emergency response) relies on before event data collection. The required frequency of monitoring must capture the dynamics of the feature of interest. Operating under normal conditions, seasonal phenology illustrates one of the slowest and hydrologic flushing and storm surge (river flooding) the fastest varying controls of coastal resources. Coastal resource phonologies should be captured at minimum, seasonally, and preferably, weekly, and coastal flooding every 2 hrs or better [30]. With systematic sampling, higher frequency sampling may be approximated. For example, linking the tidal excursion (inland extent) to the tidal stage over a single tidal cycle is unreasonable observation requirement from orbiting satellites. If the collections occur at least weekly or better over a long-time period, the tidal stages and excursions at the times of each collection may be aggregated to construct a series of tidal excursion extents that simulate a much higher collection frequency over a single tidal period. Such a systematic observation strategy is obtainable with DESDynI. Once an event occurs that dramatically changes the coastal resource, data collection frequency can be increased as appropriate to document and quantify initial damage and recovery rates and determine the nature of recovery.

Response activities when related to dramatic events, such as severe storms, floods, and fires are fairly definable in time; more protracted events that also severely and adversely impact the coastal landscapes are less definable. When initially recognized in the central Gulf of Mexico, for example, a marsh dieback episode was already spatially extensive and had progressed to a point that threatened the viability of these critical coastal resources [31]. The dieback that caused the emergency response had not suddenly appeared; the dieback occurrence had finally become observable with current observation strategies. The continuous data stream of enhanced ecosystem status indicators provided by DESDynI SAR, InSAR, and Lidar monitoring systems will promote early detection of adverse impacts (e.g., coastal resource dieback events related to prolonged elevated salinities and water logging following storm surges) and thereby, the opportunity of remediation before irreparable coastal resource loss. As in storm impact and river flooding, the strategic collection of regional DESDynI data at least weekly or better is key in detecting the onset and progression of these more subtle but widespread and potentially devastating events. At the earliest confirmation of a severe regional impact related to these events, the pre-event wide-scan collections should be coupled with higher resolution collections targeted at critical coastal zone locations. Higher collection frequencies should continue throughout the impact time period and the extended recovery period.

2.4.2 Emergency Response

The frequency of data collections in support of coastal ecosystem status and trends monitoring, including forcing function dynamics such as flooding, is intimately coupled to emergency response data collection frequency. In the year 2000, there were 83 Class 1 floods. Class 1 floods are defined as large flood events that result in significant damage to structures or agriculture, fatalities, and/or 1–2 decades long reported interval since the last similar event [23]. Rapid data delivery is key for emergency response and recovery; hence DESDynI should evaluate costs and capabilities for satellite tasking and data latencies in the realm of hours.

The wide and standard SAR swath modes coupled with Lidar waveform collections and InSAR products offer an integrated response that fits both emergency and long-term monitoring requirements. In imminent emergency situations, the official start of emergency collections is normally at the time of storm impact or start of river flooding. For DESDynI, a more appropriate data collection strategy would be to begin wide-swath collection throughout the extended-predicted impact area as soon as the National Weather Service declares a storm is threatening or when river flooding is imminent. As the storm impact or river flooding impact area is better defined, higher spatial resolution SAR data collections coupled with DESDynI Lidar collections would be concentrated in the more narrowly predicted impact zone. At and for some time after impact (dependent on damage extent and intensity), SAR and Lidar data collection should continue at short temporal repeats.

2.4.3 Coastal Oceans and Ice Event and Monitoring Response Plans

It is obvious that the orbit tracks will determine when it is possible to obtain imagery for ocean and ice hazard situations. Nonetheless, we strongly encourage no more than 1-hour latency from data acquisition (data downlink) to SAR image provided to the relevant organizations (one hour from downlink to final geophysical product production would be even more useful). We also note here that the presence of additional ground stations will minimize the time from observation to downlink. Perhaps an US East Coast ground station would be particularly valuable.

For wind, wave, oil spill, vessel and iceberg detection, and meteorological applications including hurricanes 1-hour latency is needed. Latency can be relaxed to 2-3 hours for global ice applications; however, Great Lakes and coastal ice analyses have additional benefits if produced within one hour. This could be accomplished in the future with an international constellation of satellites.

2.5 Targets and Observational Frequency

The ocean features that SAR observes well and with high accuracy, including ocean swell, wind speed, circulation patterns including eddies, and atmospheric patterns generally have short, highly varying time scales on the order of hours to a few days and often require fine resolution. Thus rapidly repeating acquisitions are generally required. Table 1 contains the presently known observational requirements for floods, ocean and coastal SAR data and derived products. No one satellite can meet all of these requirements, but the coming international SAR constellation of satellites with DESDynI as one of several satellites providing near-real-time SAR imagery and derived products will be able to meet most of the requirements. Observational priorities for hazards vary with season and circumstance, but in general sea and lake ice analyses and coastal winds in Alaska are the highest priority with imaging for known marine oil spills resulting from accidents or potential areas of spills after hurricanes also having the highest priority when they occur. For coastal ocean circulation studies, there is likely to be a broad interest in most coastal zones of North America as these areas are dynamic and impact or are impacted by the large population densities found close to the coast.

2.5.1 Coastal Resource Target Prioritization

Collections will be prioritized over United States. The highest priority coastal collections should include regions (1) experiencing rapid change, (2) often subjected to damaging natural impacts, (3) retaining critical and threatened resources, and (4) having high impact. These include the entire U.S. Gulf coast, specifically the Mississippi Delta region, the Florida everglades, the Delmarva Peninsula, Washington's Puget Sound, the

Aleutian Islands, Hawaii, and urban centers situated near the coast (e.g., New Orleans, Louisiana). In conjunction with U.S. priority collections and systematic coverage every four days, coverage of the entire globe is desired and should be developed. Included in the global coverage, coastal urban areas subjected to subsidence (e.g., Bangkok) and coastal wetlands should have priority collection frequencies. Global collection strategies should also concentrate on regions of high population densities that are located in dynamic environments, such as river deltas. Complementary U.S. and foreign programs should be incorporated within these global collection strategies that would extend and elevate the importance and usefulness of the SAR and Lidar collections. One example of a U.S. initiated program that has international partners and implications and is focused on specific coastal landforms is the USGS Delta Research and Global Observation Network (DRAGON http://deltas.usgs.gov/default.aspx). DRAGON's purpose is to create a platform for integrating specialists to address complex issues for effective and sustainable management of deltas and large rivers. Others exist and should be considered in the overall DESDynI data utilization planning.

Table 5. Floods, ocean, and coastal SAR image product requirement list.

NOAA SAR Interests	Product Name and Geographic Coverage	Purpose	Frequency	Latency	User Community
Cryo-sphere Products					
Sea Ice	Global, Alaska – ice charts and edge	Routine ice characterization and mapping	Weekly to Bi-weekly charts Daily edge	3 to 5 days 12 hours	Navy, USCG, NSF, NOAA vessels, Shipping Industry, Climate community
Sea Ice	Alaska - Shore Fast Ice Conditions – edge, condition, leads	Assessment of conditions of shore-fast ice in Alaska	Daily during spring	1 hour	Indigenous whale/ walrus/seal hunters
Sea Ice	Ice mask – for areas covered by wind and vessel detection	Automated ice/no-ice discrimination for masking out ice areas for vessel detection	For every SAR wind and vessel detection SAR image at high	0.5 hours	NWS

	products	and wind products	latititudes		
Icebergs	Iceberg detection and tracking – North Atlantic Iceberg area.	Prevent collisions of ships with icebergs	Four times/day	1 hour	International Ice Patrol, international shipping and passenger cruise industries
Oil spills associated with ice	Mapping and tracking of high-latitude and on ice spills	EEZ surveillance and spill response	Daily	6 hours	NOAA OR&R, USCG
Lake Ice	Great Lakes ice charts	Routine ice characterization and mapping	Daily and bi-weekly	12 hours 3 days	USCG, CCG, Shipping Industry
Lake Ice	Great Lakes Ice Type	Provide information on type of ice as proxy for ice thickness	3 times/week	6 hours	U.S. Coast Guard, NWS Great Lakes States
River Ice	Spring breakup river ice conditions for Alaska and Montana Rivers	Provide information on ice jams, ice runs, flooding during Spring breakup for Alaska and	3 times/week	6 hours	River communities NWS Alaska and Montana
Glacier Monitor-ing	Alaska glacier mapping and change detection	Monitoring of glacier changes related to glacially dammed lakes and changes in shoreline	Monthly – daily during ship surveys	3 hours	National Ocean Surface, NWS Alaska

Ocean Products					
Winds	Wind speed and direction for all U.S. coastal areas and adjacent seas – Highest priority - Alaska, Washington State, hurricanes	Information on dangerous coastal winds, storms/hurricanes for safety of life and property, Siting of wind farms, coastal wind climatology	As often as possible up to every 3 hours	0.5 hours	NWS, National Hurricane Center, U.S. Coast Guard, U.S. Air Force, civilian aviation industry
Waves	Swell wave significant wave height, direction, wavelength	Information on wave hazards to shipping and fishing industry as well as for shoreline erosion	Twice daily	1 hour	NWS, U.S. Coast Guard, Fishing companies, barge transportation companies
Vessels	Vessel position, size, speed, direction in selected fishing areas and approaches to selected ports and in selected marine sanctuaries.	Fishing enforcement, maritime border monitoring, protection of marine sanctuaries, oil spill monitoring	As often as possible up to hourly	0.5 hours	U.S. Coast Guard, Alaska Dept. of Fish and Game, NOAA/NMFS, NOAA/NWS, NOAA/NOS
Pollution	Oil spill on water - location and movement	Oil spill monitoring/response, wetland and marine sanctuary protection, endangered species protection	Twice daily	1 hour	NOAA/NOS, U.S. Coast Guard

Pollution	Near-shore pollution from river outflow and stormwater runoff	Public health	Twice daily	1 hour	State Agencies, EPA
Currents	Littoral surface current velocity	Search and rescue, public safety, fisheries research	As often as possible, up to hourly	0.5 hours	U.S. Coast Guard, State Agencies
Bathymetr y	Near shore bathymetry and change detection	Assessment of bathymetry changes after storms and near ports	As needed post storm or seasonally	2 days	NOAA/NOS, U.S. Coast Guard
Surf Conditions	Surf zone location, breaking wave height, bathymetry, currents (rip zone location)	Recreation and swimmer safety	As often as possible, up to hourly	0.5 hours	State Agencies
Ocean Mesoscale Features	Eddy, river plumes, upwelling, current boundaries, hazardous algal blooms, convergence zones	Marine Debris detection, fisheries studies, marine transportation, hazard monitoring	Twice daily	3 hours	NOAA/NMF S, U.S. Coast Guard, NOAA/NOS
Mixed Layer Depth	Mixed layer depth from internal waves	Fisheries studies, submersible operations	Twice weekly	6 hours	NOAA/NMF S
Atmo-spheric Products					
Atmo-spheric boundary	Boundary Layer phenomena –	Safety of aviation, marine transportation,	Four times per day	0.5 hour	NOAA/NWS, U.S. Coast Guard, U.S.

layer phenomena	barrier jets, wakes, lee waves, vortex streets, katabatic winds, gap winds, fronts	and fishing activiies			Air Force
Storms/ hurricanes	Storm/ hurricane morphology such as eye diameter, precipitation location, convection, roll vortices	Storm forecasting and analysis	As often as possible up to hourly	0.5 hour	NOAA/NWS
Hydro-logic Products					
Floods	Flood mapping – river and coastal	Analyses of flooded areas	As often as possible up to hourly	1 hour	NOAA/NWS
Land Products					
Shoreline	Shoreline mapping and change detection	Mapping shoreline changes after storms	As needed after storms	3 days	NOAA/NOS
Coastal Wetlands and Adjacent Resources	Systematic Monitoring	Mapping and Monitoring Coastal Wetland Resource Condition, Status, and Dynamics	Daily to Weekly	Dependent on the need	NOAA/NOS, USGS, USFWS, USNPS, DHS, State and local agencies

Coastal Regions including At Risk Population Centers	Emergency Response	Coastal Flooding and Severe Impacts	0.5 hrs to 2 hrs	No more than every 2 hrs during Emergency Response	NOAA/NOS, USGS, DHS, State and local agencies [29]
Boreal Forests	Systematic Monitoring	Detection and mapping of freeze/thaw timing and extent, biomass	Weekly during periods of rapid change	3 days desired for key areas to support field work	Ecosystem management agencies

3. Subsurface Reservoirs

DESDynI will be able to provide unique time-series background data over large areas that can be used to measure aquifer and subsurface formation properties, particularly with respect to ground subsidence, or uplift, from fluid withdrawal, or injection. DESDynI will provide unique observational opportunities for all of the following applications: 1) Determination of geographic distributions of reservoir changes as reflected in surface deformation; 2) Determination of the geologic structure/boundaries/fault slip based on discontinuities in uplift properties; 3) Determination of fluid pressure from uplift and fluid flow property changes; 4) Determination of thermal expansion/contraction properties over entire reservoir areas by linking *in situ* observations of temperatures with uplift data; 5) Temporal sampling over yearly hydrologic cycles and over long periods of reservoir development; 7) Determination of 3D displacement fields from subsurface fluid movements based on surface-uplift-validated modeling; 8) Contiguous coverage of the surface of the Earth across drainage basins or ecosystems to provide comparative dynamics data; 9) Making longer wavelength observations with a unique ability to look at more areas, in particular in vegetated and cultivated regions; 10) Using multiply repeated observations to improve the ability to extract small deformation signals in areas with large temporal decorrelation because of the improved potential of using PSInSAR.

DESDynI-unique opportunities include the ability to have contiguous coverage over on-land and coastal areas at long wavelengths and to compare areal properties, in particular across vegetated and cultivated regions. DESDynI can uniquely provide geographic distributions of subsurface fluid withdrawals (groundwater mining, geothermal fluid extraction, or oil and gas production) or fluid injections (enhanced oil recovery, natural gas storage, groundwater recharge, geothermal fluid injection or injected carbon dioxide plumes). The areal variations can provide information on geologic structures, fluid flow unit boundaries, and discontinuities in fluid flow units such as faults at the reservoir levels, thermal expansion or contraction responses from fluid injections/production in geothermal areas, or differential responses to fluid pressurization/ depressurization from differential uplift and compaction. The Decadal survey particularly mentions hydrocarbon-resource management and the potential importance of new subsurface applications, such as carbon sequestration as a greenhouse gas mitigation strategy, as areas in which DESDynI may have broad new societal impacts. DESDynI observational repeat intervals will provide baseline understanding of processes before, during and after subsurface system developments through broad areal coverage, repeated temporal sampling, and 3-D displacement model verification. These applications all require an accuracy of a few mm/yr over 10’s of km, spatial fidelity pixel size of 30 meters, and weekly to seasonal measurements to deconvolve the influence of shallow anthropogenic signals (e.g., groundwater) from those of deeper processes.

3.1 Applications in the Context of DESDynI

3.1.1 Hydrology and groundwater management applications

DESDynI offers a unique opportunity to improve our knowledge of the detailed mechanisms underlying hydrology and our ability to manage groundwater resources. The contiguous coverage of the Earth's surface will allow the assessment of aquifer conditions over broad regions and the frequent temporal sequences will enable scientists to capture the causes and consequences of major change events. The use of L-band radar for the SAR will facilitate ground observations in vegetated and cultivated regions. The short repeat pass cycle will permit the permanent-scatterer technique (PSInSAR) to yield results in regions where temporal decorrelation in traditional InSAR processing would introduce noise that masks the underlying deformation signal. An extended drought in the southwestern states, combined with increased population and greater agricultural and manufacturing water usage, has made effective water resource management critical to our economy and society, especially as water draw-down is often accompanied by inelastic changes that result in decreased future water storage capacity. Overall, the number of reservoirs that can be monitored, the improved accuracy of the change detection, and the frequent temporal sampling will yield a data set from which much more accurate and detailed characterization of hydrologic and geomechanical processes can be obtained than are currently available. Improved understanding of subsidence and water storage will feed into long-term water management planning, enabling a quantitative comparison of different usage scenarios and, ultimately, improved decision-making.

The principal hydrologic objective of InSAR is to improve our characterization and modeling of aquifer systems, which will lead to better-informed policy decisions about water usage and a more sustainable water supply. Aquifer-system characterization includes defining the lateral extent of the aquifer system through identification of boundaries such as faults, facies changes, and juxtaposition of sediments with differing compressibilities. Aquifer-system characterization also includes quantification of the aquifer-system properties that govern deformation such as specific storage (elastic and inelastic) and preconsolidation head. Within this context it is important to note that as fluid-filled reservoirs are depleted they may compact, limiting the potential for recharge. It will contribute to determining the response of aquifer systems to changes in water recharge over time through monthly and annual precipitation cycles. The ground deformation patterns will improve parameterization of hydrologic models based on geometric changes observable at hydrologic unit scales, and will enable inferences concerning the rheological behavior and the response of a hydrologic unit to stress and compactional deformation during water injection, or production.

The improved parameterization of the hydrologic models will be valuable since they are widely used for water-resources management. Understanding the areal extent of subsurface hydrologic units will be a critical component of understanding the sustainability of water resources locally and regionally. Inelastic deformation mainly reflects permanent compaction of fine-grained sediments and reflects permanently reduced ground-water storage capacity (lost pore space). "Water of compaction" is a nonrenewable resource available only during the first cycle of large-scale water-level draw down. Better information is needed on overall potential subsurface storage volumes, assessing changes in storage volumes in critical aquifer systems, and assessing permanent loss of storage capacity due to permanent formation damage. DESDynI has the potential to provide the spatially extensive, long-term records needed in particular the ability to infer elastic reversible changes from in-elastic changes leading to loss of pore space, by water resource managers to improve approaches to long-term management of water resources.

Large-scale, long-term changes in water storage in the Nation's aquifer systems are poorly known. Elastic deformation mapped by DESDynI in areas of active groundwater pumping can be related to recoverable changes in storage. Often the net subsidence/uplift in an area is the aggregate of changes induced by different and distinct processes. Measurements of subsidence rates at the level of 1 mm/year over extended regions can be used to improve models to combine the effects of the multiple geophysical and geochemical processes. The regular and consistent mapping of tectonic land-surface deformation by DESDynI will allow us to assess the aquifer-system response to changes in stress patterns with unprecedented spatial and temporal resolution [32-34]. This will permit us to better infer the lateral extent of key aquifers, and assess the rheological properties of aquifer systems. Accurate mapping of hydrologically induced deformation often reveals sharp boundaries that influence the large-scale response of aquifer systems and commonly coincide with tectonically significant mapped or unmapped faults (cf. Las Vegas and many basins in southern California [35-38]).

It is also critical to understand the hydrologic signal in the total deformation pattern in order to extract the signature of other processes (seismic, tidal, etc.). In regions where there are large seasonal (or other) variations in ground-water levels, hydrologic effects tend to dominate the total deformation signal. This is often the case even where the tectonic signal is relatively strong (again cf. Southern California, where the tectonic signal is typically ~1/10 the hydrologic signal). Thus understanding the hydrologic signal is crucial to extracting the signature of other processes. Longer-term observations with regular repeats enable the non-hydrologic responses to be better identified.

InSAR can also provide important information about sedimentation and surface water transport phenomena objectives including measurement of sediment flux in river systems, resolving surface water flow in arid regions, measurements of 4D sediment volume change associated with natural and catastrophic surface water flows, and characterization of sediment pulses associated with changes in surface hydrologic flows such as dam water releases, flooding, etc. Repeated measurements can identify the spatial extent of river flows in arid regions where episodic rainfall events drive the system and estimate the water volume discharge in rainfall events.

3.1.2 Subsurface hazard mitigation applications

InSAR data from DESDynI will enable routine, regional-scale monitoring for early warning of potential infrastructure failures derived from subsurface causes. Land subsidence has caused water-supply wells to collapse, railways and roads to be damaged, and water, oil, gas, sewage, and storm drainage conveyance facilities—particularly gravity-driven ones—to fail. An example of subsurface changes causing damage is the Mexico City sewage system failure where subsidence caused by groundwater dewatering caused changes in the pitch of the sewers and reversal in sewage flows [39]). Subsidence can also be a major threat to water and oil conveyance facilities, transportation infrastructure and water well stability as well as storm drainage.

Data from DESDynI will be able to provide long-term baseline elevation information and enable routine monitoring of other water system infrastructure. Variable subsidence in compacting coastal areas has proven to be a threat to levees, and detecting areal patterns of subsidence near levees can be indicative of increasing stresses that may lead to failures. A related objective is to protect ecosystems from change due to subsidence. For example, subsidence can dramatically affect flooding patterns, potentially altering water flow or collection in ecosystems with low topographic relief.

3.1.3 Oil and gas reservoir management applications

Hydrocarbon reservoir management focuses on modeling and balancing of production from multiple wells to maximize recovery and through that economic management of the reservoir(s) to increase production while minimizing costs. In general optimal and efficient reservoir management includes extraction of reservoir fluids often enabled by injecting other fluids at other points in the reservoir. Both the injection and extraction processes lead to surface uplift (at injection sites) and compaction phenomena (at producing sites) and are often observable from InSAR data.

Our country still relies on fossil fuels for the vast majority of its energy needs. Currently our estimated reserves of energy are decreasing over time and it is critical to maximize production. A major challenge to optimize reservoir management is related to reservoir heterogeneity. Subsurface rock unit heterogeneity affects greatly the fluid pressure distribution in the subsurface but is often only partly known. InSAR technology can aerially register deformation related to oil and gas production at relevant spatial resolution. In particular such deformation may be used to infer pressure and saturation changes due to production and injection. In particular these changes can further be used to identify regions of bypassed oil and gas and to image reservoir heterogeneity. Temporal and spatial variations in surface displacement can be used to constrain reservoir mechanics and identify the fundamental processes controlling reservoir geomechanics. Furthermore, one may relate strain changes to stress changes and induced seismicity in the reservoir and thus provide key information of potential loss of well integrity due to sudden changes in local stress distributions.

Currently, seismic imaging using surface geophysical sources and receivers is the method most relied upon to provide information on subsurface structure and heterogeneity, which however, is not always providing this information at the relevant scale or leads to significant environmental impact. Analysis of surface displacements using InSAR data provides independent, cost-effective data to improve knowledge of the subsurface structure [40, 41].

Thus, InSAR provides a number of opportunities to better meet hydrocarbon reservoir management objectives, including: a) Characterizing reservoir properties remotely, and spatially extensively to maximize production; b) Determining fundamentals of reservoir mechanics; and, c) Relating strain changes to stress changes and seismicity; d) Improving our modeling of subsurface reservoirs; and e) Improving modeling of geophysical and geochemical processes related to subsidence/uplift.

Of course, hydrocarbon reservoirs have been managed for over a hundred years by state and federal agencies based on the best available data site by site. However, new data types, which will be provided by DESDynI over large areas with regular repeat cycles, will afford unique new opportunities to manage natural resources. In particular, because of uniform areal coverage and the ability to track subsurface processes over time, satellite missions may well be a critical factor to redeveloping older oil and gas properties in the lower 48 states where billions of barrels of stranded oil and gas reside in old oil fields.

An important requirement for hydrocarbon production (and CO2 storage) is the deconvolution of surface deformations resulting from multiple sources in the same target area. Hydrocarbon reservoirs, as well as CO2 storage reservoirs, are located deep in sedimentary basins where shallow groundwater is often also produced. Water produced during hydrocarbon extraction is often re-injected into shallower geological formations providing another potential source of surface deformation. Rain events can lead to shallow groundwater pressure increases and surface deformation changes. Tectonic surface movements can also be superimposed on the deformations produced by reservoir management activities.

3.1.4 Natural gas storage applications

InSAR can be used to measure deformation of the Earth's surface associated with the injection of natural gas at depth. Areal deformation patterns can monitor the stability of gas injection sites at depth and to track the migration of gas laterally. Repeated measurements over time can provide information on the stability of reservoirs through multiple injection production cycles. Natural gas storage application objectives include better characterizing reservoir properties to maximize production, improving recovery of seasonally injected and reproduced gas and improving reservoir management to lower costs and improve reliability.

Typically, natural gas required for winter heating needs is produced during the summer months and transported to regional sites where it is stored in large underground reservoirs (usually depleted oil and gas fields). As with any natural geologic system, such reservoirs are heterogeneous and the detailed geometry uncertain. This uncertainty can result in the loss of a significant portion of the injected natural gas through leakage into the surrounding formations. The volume change and consequently the pressure change associated with the injected gas gives rise to deformation which may be used to estimate the geographic distribution of the gas plume and to design better recovery and management practices. Furthermore, as has been shown also elsewhere in Europe [42] seasonal storage of natural gas in smaller nearby reservoirs from a larger natural allows for maintain optimal reservoir pressure thereby stabilizing compaction responses. This reduces risk of sudden surface deformation events related to gas production.

3.1.5 CO_2 sequestration applications

The major objective of InSAR for CO2 sequestration is to track the surface deformation associated with injected CO2 plume and its associated pressure front to assure containment. In this sense it is similar to gas-storage applications discussed above and to reservoir management applications in general.

Geologic CO2 sequestration is the long-term storage of carbon dioxide in the subsurface as a trapped gas, liquid (dissolved), or solid (mineral) phase through biological or physical/chemical processes. CO2 can also be captured as a pure by-product in processes related to petroleum refining and power generation. Carbon capture and storage refers to the large-scale, permanent artificial capture and storage (sequestration) of industrial produced CO2 using subsurface saline aquifers, reservoirs, ocean water, and other sinks (Intergovernmental Panel on Climate Change, 2005). CO2 sequestration has been proposed as a way to mitigate the accumulation of greenhouse gases in the atmosphere released by the burning of fossil fuels. Subsurface CO2 injection has been used for several decades in enhanced oil recovery methods for tertiary recovery in older reservoirs, and that use has been proposed to be significantly expanded as well.

CO2 sequestration will be probably be mandated as one of the acceptable options for climate change mitigation for fossil-fuel-using industrial and power facilities under EPA and State regulation for underground injection control operations. It will be regulated under a new UIC class – Class VI, which will require validated computational modeling as the foundation for area of review determination, operational parameters and site-closure responsibilities. As such, InSAR can provide unique capabilities to the monitoring, validation and carbon credit accounting metrics for the industrial implementation of this option. To be effective, CO2 sequestration will be implemented eventually at most major CO2 producing fossil fuel using facilities, which will number in the thousands across the United States.

Injection of CO2 as a greenhouse gas mitigation strategy will require injection of billions of tons of CO2 into depleted oil and gas fields and deep saline formations [43]. The supercritical CO2 will spread out from the injection well associated with each CO2 source and form a low viscosity buoyant subsurface plume that will displace from 1%-3% of the fluid volume in the sequestration formation and will be associated with a pressure front displacing the native brine ahead of it. CO2 injection associated with enhanced oil recovery has been successfully tracked through InSAR observations. InSAR can provide long-term, long-wavelength tracking of the orientation and magnitude of the pressure front and CO2 plume that will be required to validate modeling of the sites that will be required by underground injection control permits [44].

3.1.6 Geothermal energy applications

The principal objective for InSAR use in geothermal areas is to understand subsurface properties to maximize heat recovery and minimize risks of fluid loss or damaging seismicity. InSAR data have also been used to evaluate subsidence related to production of geothermal brine and steam [45-49].

Geothermal reservoirs, being located in volcanic regions, are particularly heterogeneous systems. Thus, successful geothermal production is critically dependent on characterizing the controlling geologic features of the reservoir. Accomplishing this is made more difficult by the fact that geothermal field operators often do not have the financial resources to mount an extensive characterization effort. InSAR can be an important tool for cost effective reservoir characterization [44]. Compared to other geophysical techniques, InSAR is relatively inexpensive. Furthermore, it is a time-lapse method, sensitive to pressure and temperature changes due to the production and injection of geothermal fluids. Thus, it is influenced by the deformation of fractures and faults controlling flow in the reservoir.

3.1.7 Ecosystem protection applications

InSAR can provide information in areas particularly sensitive to the effects of subsurface-process-driven subsidence on the ecosystem, including coastal ecosystems. L-band imaging is more sensitive to subsidence in these areas and thus is particularly well suited to be used for this application.

Coastal ecosystems are particularly vulnerable to the effects of land subsidence. In the Florida Everglades, where several feet of peat-soil-oxidation is common, only ½ foot of land-surface elevation difference may distinguish a tree island from a sawgrass plain. In the Galveston Bay area, more than 26,000 acres of wetlands were lost to subsidence caused by groundwater pumping. The regular L-band coverage provided by DESDynI will dramatically improve our ability to recognize, map, and monitor topographic changes in heavily vegetated coastal wetlands.

3.1.8 Public outreach and education

DESDynI mission products will be able to have a significant application in public outreach and education by providing large-scale observational databases of land- surface-change dynamics linked to studies of subsurface processes. The large amount of data that will rapidly become available, however, could also cause some public relation problems as property owners increasingly can identify their property within the context of local, state and regional activities. They may perceive a negative effect on real estate values from derived products such as ground surface elevation changes reflecting hydrologic changes in deep aquifers, or the extent of injected CO_2 plumes. To proactively counter this, it would be prudent to encourage public education programs in the years preceding launch and the first year of operation through organizations such as AASG, GSA, AGI, etc. This may decrease the negative press that might otherwise occur when landowners see local geologic hazards illustrated in a graphic manner.

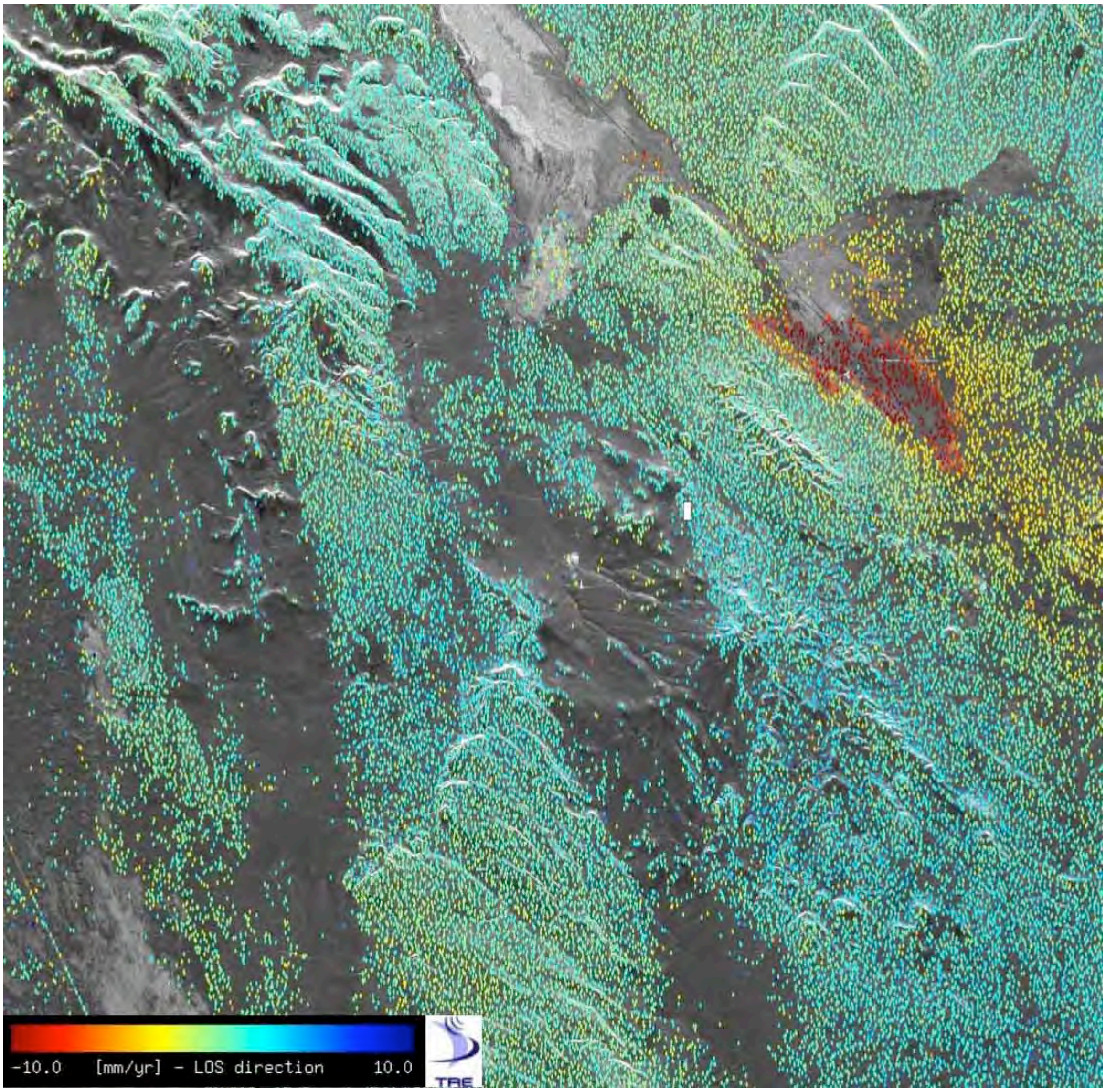

Figure 14. This figure shows the range of velocity variations over the Brady's and Desert Peak geothermal fields. The subsidence associated with production at the Brady's field is clearly indicated in this figure.

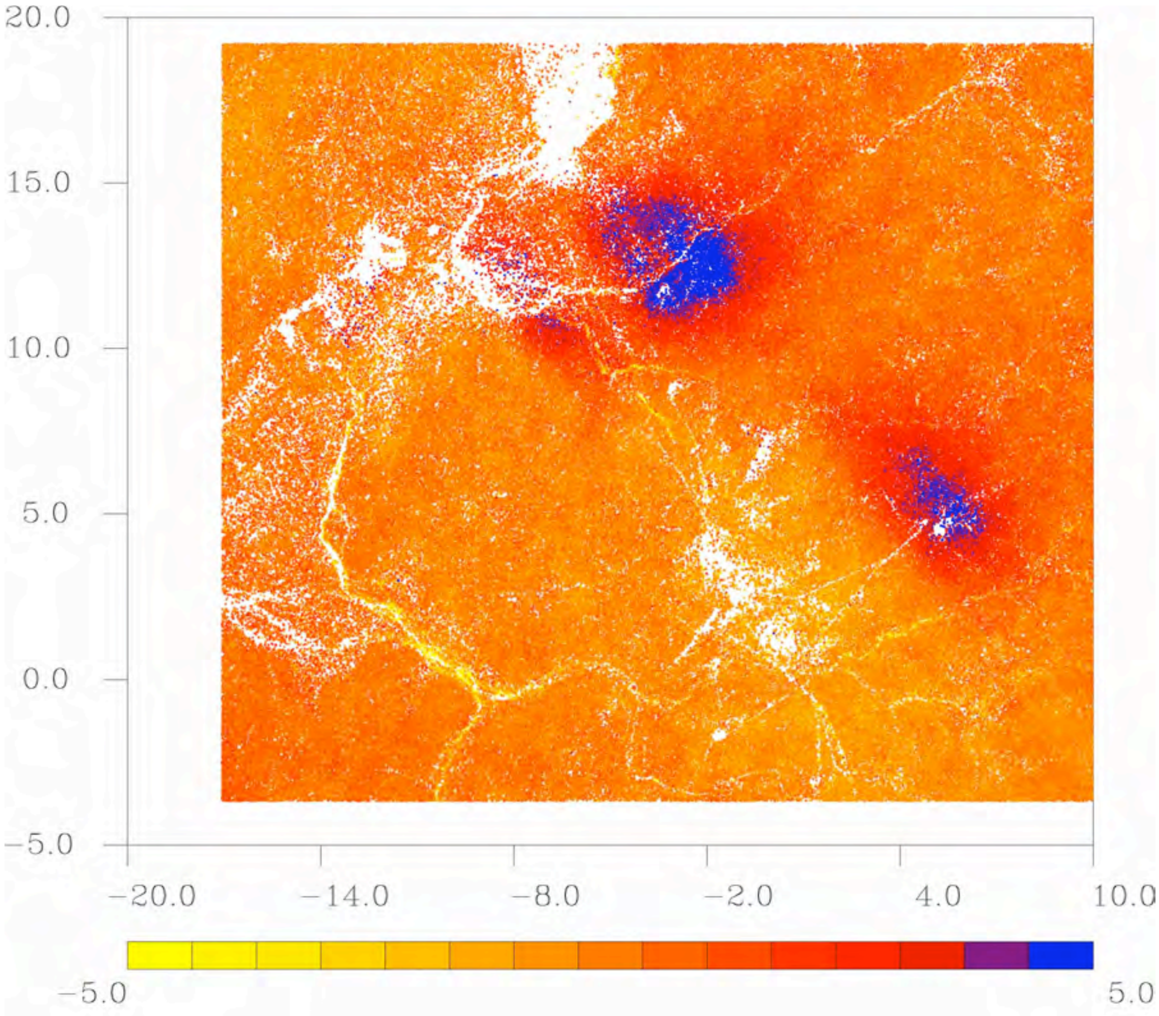

Figure 15. Range change estimated from Envisat InSAR data indicating uplift due to the injection of CO_2 into three wells at the Krechba field, Algeria.

3.2 Goals, Objectives, and Observation Needs

3.2.1 Goals

Hydrology

In hydrology the objective is to determine the response of aquifer system to changes in stress, fluid pressures, and fluid distributions during injection or removal. This will include inferences about the lateral extent of the aquifer system and the formation rheology. DESDynI will enable improved parameterization of hydrologic models for predicting aquifer properties, and improved understanding of the hydrologic signal in the total deformation pattern in order to extract the signature of other processes (seismic, tidal, etc.). Hydrologic signals often dominate the signature in areas where competing processes contribute to the total deformation, and where the primary interest is in studying the non-hydrologic processes. In order to assess the sustainability of water resources, we need to assess changes in storage in critical aquifer systems, assess permanent loss of storage capacity due to elasticity changes, and provide better information to water resource managers for long-term management of resources.

Hydrocarbon Reservoir Management

For hydrocarbon reservoir management the objectives are better economic management of hydrocarbon reservoirs, increased production, and reduced environmental impacts from operations and produced water reinjection (an average oil well produces 3-8 barrels of water for every barrel of oil, which must be reinjected or treated). More efficient hydrocarbon production will lower costs and reduce dependence on foreign sources.

Although most easily produced oil is now gone, substantial hydrocarbon reserves still exist. The challenge is how to produce these reserves efficiently and economically. Here we focus on two examples of known reserves.

First, when oil is pumped out of the ground, only about a third is typically removed, with about two thirds left trapped in regions of less permeability or in regions isolated from the well. Decreasing the amount of oil left behind, even by a small fraction, would substantially increase the amount of oil that could be produced domestically. Active management leads to substantially improved extraction efficiency. Techniques include hydrofrac to increase reservoir connectivity and flooding by water, steam, or CO_2 to actively push oil toward the well. One of the big challenges faced in reservoir management is to areally "observe" the spatial and temporal patterns of fractures and increased fluid pressure. For reservoirs within a few km of the land surface, these changes in underground plumbing and fluid pressure lead to surface deformation that would be observable by DESDynI.

Second, production of unconventional hydrocarbons, e.g., oil sands and tight gas, is becoming increasingly important. Such production also involves injection of high-pressure fluids (steam) to heat the oil and drive it toward production wells. The resulting underground pressure variations lead to variations in surface deformation that are directly observable via InSAR.

Finally natural gas storage in depleted reservoirs is increasingly used for optimal gas production from the (main) producing reservoir. The associated uplift and compaction will be observable from DESDynI and hence will provide important information on the elastic response and storage integrity of the reservoir potential.

Climate Change Impacts Mitigation

Another increasingly important problem for society is the possible mitigation of climate change effects by the capture and sequestration of greenhouse gasses. Implementing this CO_2 sequestration option depends upon overcoming significant technological and policy challenges. The objective for imaging CO_2 sequestration sites is to better characterize potential sites for injection and to provide performance assessment of operating CO_2 sequestration sites. Repeated InSAR observations will enable improved subsurface reservoir models for site characterization and development prior to injection. They will provide assurance of integrity of CO_2 sequestration during and after injection, and provide a better foundation for post-closure monitoring to reduce costs and establish the appropriate areal extent and invasive sampling strategy to support closure.

DESDynI would contribute significantly to the challenge of verifying containment. Injecting CO_2 is associated with subterranean pressure increases that lead directly and quantifiably to surface deformation. InSAR has already been shown to be capable of determining the pressure variations associated with the migration of injected CO_2.

The societal benefits of improve sequestration operations will be to lower costs of this greenhouse gas mitigation strategy, build public confidence in this technology option and expand the acceptable areas for implementation of this option for climate change/greenhouse gas mitigation.

Protecting Infrastructure

The objective in using InSAR observations to protect infrastructure facilities is to detect surface change induced by subsurface reservoir changes prior to catastrophic failures. Better observations will be used, to protect water, oil, natural gas and other conveyance facilities, to maintain the performance of engineered water infrastructures at the regional and local scales, particularly sanitary sewage and storm water drainage, to protect transportation infrastructure, to protect subsurface water sources accessed by wells, to detect surface elevation changes, particularly subsidence near levees that are indicative of increasing stress, and to provide baseline height information in critical regions such as over levee networks.

Protecting Ecosystems

InSAR observations have a significant role in protecting ecosystems through providing subsidence information in areas particularly sensitive to their effects on the ecosystem, such as coastal ecosystems. L-band imaging is more sensitive to subsidence in these areas. In addition, DESDynI observations of ecosystems and surface elevation changes may have uniquely valuable contributions to make over the large areas of permafrost in upper latitudes that may be threatened by climate variability or long-term climate change. It can be used to track changes in the global permafrost spatial extent, quantify coastal erosion or track coastal changes associated with climate change at high latitudes, measure subsidence/uplift in permafrost regions and relate to permafrost thawing, water drainage, and oxidization of organic material and its inferred contribution to the greenhouse gas release.

Surface Water Dynamics

The objectives of DESDynI observations applied to surface water dynamics include establishing long-term areal relationships among surface water flows, surface water sediment transport dynamics and groundwater resources. Observations can measure 4D sediment volume change associated with natural and catastrophic surface water flows, characterize sediment pulses associated with changes in sedimentation (dams, floods, etc), identify the spatial extent of river flows in arid regions where episodic rainfall events drive the system, and estimate the water volume discharge in rainfall events.

3.2.2 Observation Needs for all of these objectives:

Repeat pass L-band radar is needed for surface elevation change detection. The resolution required will be 30 m x 30 m in the horizontal direction and vertical change detection should be no less than 5% of signal or 1 mm/yr. Accuracy is needed of a few mm/yr over 10's of km, with a spatial fidelity or pixel size of 30 meters, repeated weekly to seasonally to deconvolve the influence of shallow anthropogenic signals (e.g., groundwater).

3.3 DESDynI Data Products and Required Ancillary Data

3.3.1 Data products:

LiDAR

- DEM (data gaps problem?) (MS)

A precise digital elevation model (DEM) is useful for nearly all earth surface science applications including processing of interferograms. The variable atmospheric density associated with different altitudes is a significant error source and must be well-defined and removed from the radar signal to permit analyses of other phenomena, Potential data products from either a DESDynI tandem mission or the DESDynI LiDAR instrument would be extraordinarily useful for those needed precise elevation maps for myriad of earth-surface studies.

InSAR

- Level 0 (raw) data availability within 1 day of acquisition
- Level 1 (focused) data availability within 1 day of acquisition (for hazard response
- Completed interferometric product with metadata (geotiff, shapefile)
- Single/stacked/psinsar/timeseries

Level 0 (raw) data is needed to enable the management of the numerous parameters for InSAR processing for use in standard applications and scientific research. Because of the minimal treatment needed, the data should be available within 24 hours of acquisition.

Level 1 (focused) products are needed for several applications including hazard response. For a flood, for example, before and after images can help first responders identify inundated urban areas or transportation corridors.

Level 2 and higher products are needed for users who need deformation information but don't have in-house capability of managing and processing Level 0 data. These products include single and stacked interferograms, deformation maps constructed from persistent scatterers, and deformation time series derived from analyses of stacked or persistent scatterer results.

- Line-of-sight change within 3 days

With an 8-day repeat orbit, every point within the regions covered by the DESDynI InSAR would be observed at least every 4 days on either an ascending or a descending pass. Detection of change in LOS should be provided soon after the data are downlinked.

Reservoirs have been observed to deform significantly on sub-weekly time scales. Information on this deformation is needed for active management programs. The latency in monitoring changes should not exceed the interval between observations.

- 2-D or 3-d vector displacements available within 3 days of last acquisition

3-D vector displacements require obtaining changes in LOS in at least 3 nonplanar directions, with the 4 look directions that could be provided by both left- and right-looks on both passes leading to a more accurate, overdetermined solution. Combining observations on ascending and descending passes with the same look direction will allow determination of 2-D deformation in the plane including the two look directions. It is not clear at this time whether more frequent 2-D sampling or less frequent 3-D sampling will be most valuable for reservoir monitoring. In either case, the 2-D and/or 3-D vectors should be provided soon after acquisition in order to be useful for reservoir management.

- PBO model for screening data

Most of the end-users of this application of DESDynI observations will be hydrologists, reservoir managers, and people responsible for enforcing regulations and setting policy. These users will not able to process raw data; they need analyses of deformation provided by expert data analysts. Because ionospheric and tropospheric disturbances can be misinterpreted as surface deformation, release of, for example, automatically generated interferograms alone could be problematic. For that reason, DESDynI should provide estimates of ground deformation accompanied by quantitative information about the reliability of this interpretation. The model provided by EarthScope's GPS time series should be considered: Two independent data analyses are vetted and merged by a third party, with inconsistencies and possible problems flagged.

- Quick-look interferometric processing (level 2) with confidence rating

More sophisticated users will probably prefer to do their own analyses. To facilitate this, the standard DESDynI analysis procedure mentioned above should also provide quick-look data quality checks, providing information about any problems in the data that might make further analysis of a particular scene problematic.

- Velocity measurements every 6 months

For some applications (e.g., long-term CO_2 sequestration monitoring), deformation rates are expected to be slow enough that only seasonal to semiannual updates may be required. But even for slow deformation, frequent observations will improve accuracy by averaging out noise. Further, there are likely scenarios where images taken, say, six months apart would decorrelate, but deformation rates could still be accurately determined by comparing more frequently sampled images that are taken close enough in time that they maintain coherence. The optimum way to combine frequent observations in order to obtain rates over longer time intervals involve trades of averaging noise vs. loss of coherence. These trades are likely to be done best by experts, not end users. Thus

DESDynI should provide deformation time series and rates obtained by experts to end users.

Web Page

- Select area for processing
- Data request history for potential collaborations among disciplines…solid earth/hydrology/ecology
  - Not necessarily individual, but institution
- Low latency is important for active reservoir management: ASR/hydrocarbons/carbon sequestration/mine collapse warning
- Latency is less important for typical land subsidence/uplift studies

Latency is important for management of reservoir operations such as hydrocarbon production, injection and withdrawal of stored gas, or injection of CO_2 for sequestration, where engineering decisions are needed on a daily basis. It would also be important for hazardous events that can potentially occur in reservoirs. Data would be required as soon as possible in these cases, but within 24 hours is sufficient.

Latency is less important for long-term subsidence/uplift studies. However, because of temporal decorrelation, atmospheric noise and unexpected behavior, a survey frequency of 4 days will greatly enhance interpretation of measurements, and, correspondingly, a latency of 24 hours would be desired.

- Ascending/descending; left/right look
  - 3-D vector displacements
- System to prioritize potentially competing requests (reorientation, polarities vs. more global/consistent coverage)

3.3.2 Ancillary Data

From DESDynI

- Precise orbital files released soon after data release (InSAR)
- Atmospheric/ionospheric corrections

From other sources

- Geodetic control (4-D)
- Leveling/GPS/tiltmeters/extensometer
- Seismic
- Precision gravity

Seismic data can provide essential information on the structure of geologic formations defining a reservoir. In addition, using coherence cube techniques one can identify the important faults and fracture zones within the reservoir volume. In time-lapse mode, in which changes in seismic amplitudes over a given time interval are estimated, one can extract saturation and pressure changes in a reservoir due to production and injection. Such information is an important complement to estimates of surface deformation due to pressure changes in the reservoir.

- Pore-fluid pressures/water-level data
- Precise DEM
- Weather conditions at time of acquisition (NOAA)
- Geologic data

Geologic data – Geology and geophysics

Successful modeling (simulation, prediction) of compaction-related subsidence requires not only mapping of current deformation but also accurate knowledge of the "preconsolidation stress" and the distribution and rheology of compaction-prone material. The notion of preconsolidation stress reflects the fact that, in typical alluvial basins, the historical stresses are generally somewhat larger than the pre-development effective stresses. Thus subsidence only becomes obvious after substantial water-level declines have initiated inelastic compaction. From this point on, predicting the progress and ultimate extent of subsidence requires knowledge of the hydrostratigraphy, namely the distribution and rheological properties of fine-grained materials. Such knowledge derives mainly from geologic mapping and geophysical surveys. The geologic history of an area is the major determinant of the pre-consolidation stress.

- Lithology/geophysics
- Community forum (result sharing)

Community forum – Result sharing

Multiple processes will contribute to the total deformation signal mapped by DESDynI, and input from multiple user communities may often be required to clarify (extract) the signature of a particular process. Thus we should promote an open, web-based user's forum to enhance awareness and communication between (and among) disparate groups such as biologists, hydrologists, and solid-Earth scientists.

- Ground-cover/vegetation data
- Hydrology, ecosystem information
- Recharge event/leaf on or off
- Field observations/high resolution optical: changes in the built environment (e.g., well house built/oil platform removed)

Reservoir applications require a layered "data interpretation and analysis" approach in which ground cover/vegetation layers, built infrastrauctures layers and aquifer hydrology layers are subtracted systematically from the InSAR signal to allow interpretation of subsurface reservoir processes from ground deformation measurements. Ground-based biological, hydrologic, geological and geophysical observations will be needed to calibrate the interpretations of these data layers.

- Weather conditions at time of acquisition (NOAA)
- Phenology from National Phenology Network

3.3.3 Can objectives be met without ancillary data?

- Generally not without at least some ancillary data.
- With ancillary data, all objectives can be met.

3.4 Monitoring and Event Response Plan

3.4.1 How soon after an event must a region be surveyed with DESDynI

For a deformation event such as an earthquake or reservoir 'leak', ideally the area should be imaged during the next several satellite passes. At a minimum, observations are needed within 4 days. Even for longer term monitoring, because of temporal de-correlation and atmospheric noise, and unexpected behavior, the areas of interest should still be sampled as finely as possible. For long term monitoring regular long time sequences are required, and continuity is important.

There are various types of events that result in surface deformation. Some are potentially hazardous, such as an earthquake or a sudden release of gas or oil from a hydrocarbon reservoir, and some are sudden but related to effective reservoir management such as changes in injection pressures in enhanced recovery operations or the onset of injection or withdrawal of fluids from new wells. For these events surveys as soon as possible are desired, but, by the next satellite pass, or within 4 days, is sufficient.

Monitoring for gradual deformation changes is, however, very important in all applications. Survey frequency of a month will provide useful data. However, because of temporal decorrelation, atmospheric noise and unexpected behavior, survey frequency will greatly enhance interpretation of measurements. For long term monitoring, regular, long time sequences are required, so continuity is also important.

3.3.1 What types of measurements and observations are needed?

We need high frequency sampling to capture variations related to an event, and 4D measurements of displacement.

3.3.2 How will the data be disseminated and to what agencies

Geo-referenced images (readable by ArcInfo), web-accessible imagery is necessary as a data product. Due to the complicated nature of radar data processing, there is insufficient time or training for state and local users to become adept at processing during an emergency. Therefore providing raw data will not be sufficient. Products should include a minimally-processed image in a georeferenced format compatible with most commonly used GIS software. Georeferenced imagery can be used as a base for appropriate vector layers.

As of now, there is no paradigm for identifying all of the relevant state and federal agencies or their appropriate divisions to whom to deliver this information. It is expected that as InSAR and LIDAR data become more common agencies will develop new applications to their interest areas. New technologies such as carbon sequestration fall into a gray zone of bureaucratic rulemaking. Because no well-defined regulatory order exists, there is ambiguity as to who should be notified about hazardous events resulting from new technologies. Making the data easily available to a broad audience, in a commonly used format, would allow for diverse portions of government to access the data in an emergency, even if they have not been previously identified.

This information is of great value but we need to set up the infrastructure for information exchange in advance of launch with the relevant state and federal agencies. Optimal use of data for different applications will be based on experience when users have used data on a regular basis, prior to an emergency. A regular exchange of data between creators and users of data will facilitate usage during an emergency. By providing data on a regular basis interested agencies that have not been included in previous activities may be identified and software/hardware incompatibilities will be identified in advance.

3.3.3 What is the latency required for the data to be useful?

Within 24 hours of acquisition.

3.3.4 Use case scenarios

Subsidence Gradient Across Fault

Regional InSAR survey reveals previously unknown subsidence gradient across a fault, potentially effecting water transport in a canal

In this event we must insure continued data collection and provide information to the appropriate agency.

Unexpected CO_2 Migration in Reservoir

CO_2 sequestration monitoring using InSAR has revealed unexpected migration along faults and/or fractures within the reservoir.

The injection of CO_2 into the ground as part of a geologic storage program constitutes a transient event which may give rise to observable surface deformation and consequently, to InSAR range changes over time.

The sudden introduction or withdrawal of a significant volume of fluid gives rise to transient pressure propagation, which migrates diffusively into the surrounding formation.

The pressure changes lead to volume change within the reservoir, which in turn propagates elastically to the surface of the Earth, leading to the displacement of the surface.

The orbiting DESDynI satellite records the range change associated with the displacement.

The range change appears as a phase shift between the SAR images at two different orbits.

Sets of SAR images are transmitted to a user who processes the data to extract a phase shift and its variation in space and time.

An anomaly associated with deformation is then identified and may be used to infer something about the migration of the CO_2 at depth.

It is important to note that problems may be created by information overload, serendipitous "discoveries," and the need to provide concise, correct, but not lengthy explanations to the public and regulators, particularly as new technology opportunities are introduced to new agencies, local and state agencies and the public.

3.4 Targets and Observational Frequency

The major targets for subsurface reservoir observations include the major continental sedimentary basins and hydrologic basins where fluid withdrawal or injection can result in surface deformation. Other major basins may include polar and permafrost regions where land use changes may trigger or accelerate surface deformation.

Subsidence/collapse vulnerability exists in most of US, as illustrated by: 1) Maps showing major alluvial aquifer systems in the US, indicating areas where subsidence has been attributed to ground-water pumpage. 2) Maps showing distribution of salt and gypsum, which underlie about 40% of the conterminous US and which are produced by subsurface mining that may trigger surface collapse. 3) Maps showing carbonate karst landscapes, which comprise about 40% of the US east of Tulsa, Oklahoma. 4) Maps showing distribution of organic soils in the US, most of which occur along the Gulf Coast or in the northern contiguous US and Alaska. These are susceptible to peat-soil-oxidation subsidence [50].

The ideal observational frequency may vary among applications but for any surface deformation observations it is important to develop a baseline understanding of Earth surface dynamics areal around areas of interest prior to any expected deformations since difference images are far more powerful tools than simply multiple post-deformation measurements.

- After an event observations within 4 days are needed to establish a baseline, which can then be updated as often as needed to maintain accuracy.

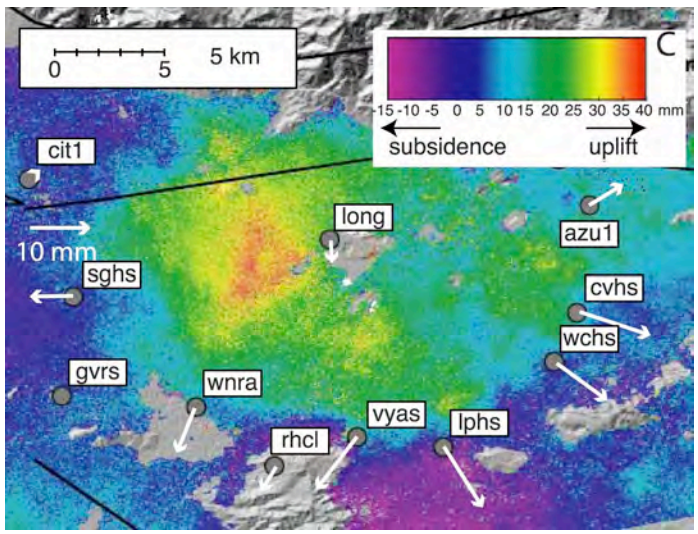

Figure 16. The January through April, 2005 horizontal GPS motions and January to July 2005 InSAR interferogram converted to horizontal motions for the San Gabriel Valley. The annual signal has been removed showing the residual motion during those time periods. Figure from [51].

Deformation associated with changes in aquifers can occur on timescales of a week or less as observed for the San Gabriel Valley in 2005 (Figure 16) [51]. We lack the observational base to know how frequently these "events" occur. Therefore we require that a large sample of aquifers in a variety of settings be made at the onset of the mission. Decisions on whether to continue the requirement for frequent sampling will be made after this initial inventory.

We know that important changes occur on seasonal and shorter time scales. Observations must be made with sufficiently high frequency to attain the required accuracies of 1 mm/yr. Studies that have addressed how frequent measurements increase the signal to noise of rate estimates suggest that weekly measurements improve the accuracy of seasonal variations by at least a factor of two.

- Similarly it is important to characterize surface characteristics over an aquifer, reservoir, or area of tectonic deformation for at least a year prior to injection or production, or sequestration programs. High resolution/frequency baseline measurements are need at the onset of a mission. Accurate DEM needed.

To understand ground surface deformation induced by changes in aquifer storage or reservoir development it is important to understand the unperturbed system prior to inducing these changes. An accurate DEM model will be an important part of site planning and initial site characterization. At least a year of data will be needed to understand annual variations related to seasonal hydrologic changes or to index average rates of slow tectonic deformation. It is likely that early reservoir operations will need higher frequency repeats to understand initial processes, and the repeat frequency may be decreased as operators and regulators become more comfortable with operational parameters.

- US, North America and then global, aquifers and early sequestration projects are high priority targets. Target regions of decline in water availability.

Targets in sedimentary basins of the United States, and North America in general, are of highest priority, followed by global targets. Aquifers in regions with declining water availability are highest priority.

Potential new applications of InSAR include managing and monitoring geological carbon dioxide sequestration sites driven by introduction of a carbon tax or other greenhouse gas mitigation measures. The DOE Office of Fossil Energy has identified at least 4,600 major carbon dioxide emitters in the United States, which put out roughly half of the US total CO_2 emissions of 6 million metric tons a year [52]. The economic impacts of sequestration requirements on energy in a "carbon constrained world" are very high. Early CO_2 sequestration projects in the sedimentary basins of North America, and few globally, are also of highest priority to develop baseline monitoring measurement and verification techniques to be applied later in the industrial sector.

4. Forest and Ecosystems Management

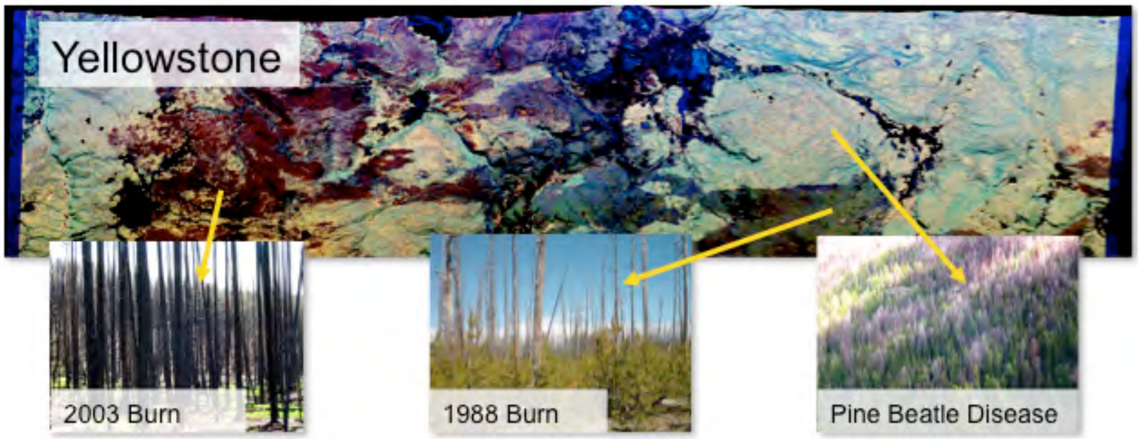

Figure 17. InSAR can be used to determine forests types and structure and indicate disturbance from storms, fires, or invasive insects.

4.1 Applications in the Context of DESDynI

4.1.1 Biomass and vegetation structure

DESDynI can be used to characterize terrestrial ecosystems with respect to biomass, biodiversity, and disturbance/change through time and provide unique observations of ecosystem type and structure. It can also be used to provide imagery for various short-term events such as floods or wildfires or longer-term events such as drought and insect outbreak impacts on vegetation (Figure 17).

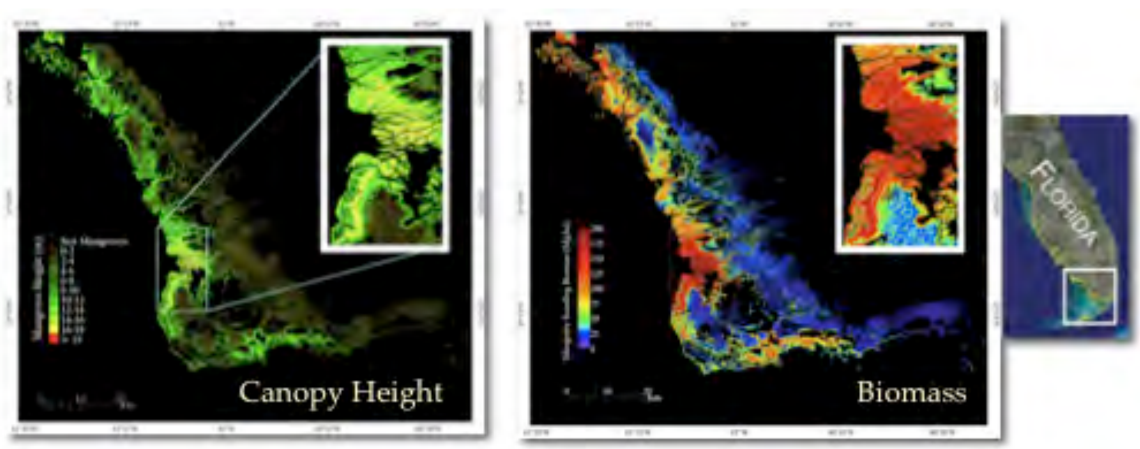

Figure 18. Mangrove forest height and inferred biomass density from SRTM calibrated with LIDAR (ICESat/GLAS and airborne) and field data. Mangrove ecosystems contribute 11% of global total carbon export to the ocean and mangrove forests are in danger of being lost entirely due to economic development and sea level rise. 35% of mangrove forests have disappeared and 60% could be lost by 2030 [53].

4.1.2 Ecosystem Health and Management

DESDynI will allow for the acquisition of quantitative and spatially precise estimates of aboveground biomass at the global scale. These DESDynI based estimates will be calibrated with and validated against field-based measurements of canopy height, vertical structure, basal area, and the horizontal (spatial) distribution of these vegetation attributes. After the establishment of a global baseline, repeat monitoring will provide information on forest dynamics and, consequently, quantify and geographically locate carbon fluxes in order to identify which ecosystems and landscapes are acting as sources and sinks of CO_2 (Figure 18). The mission is consistent with the goals of the Decadal Survey and is fully integrated with the GEOSS goals.

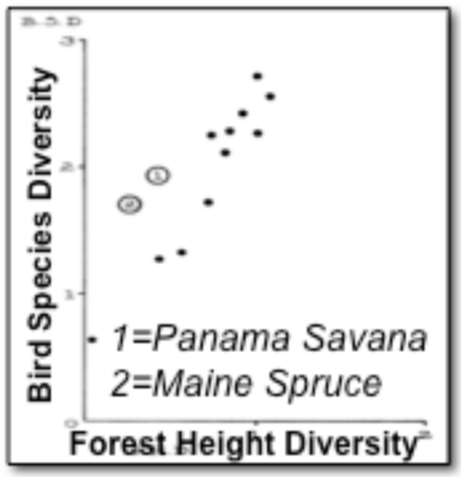

Figure 19. Forest height diversity correlated with bird species diversity. Environmental parameters such as vegetation structure correlate with biodiversity. Biodiversity decline a key issue in conservation biology [54].

4.1.3 Biodiversity

Biodiversity relevant to DESDynI applies to both plants and animals. The global grid of LIDAR vegetation profiles will provide terrestrial ecologists and conservation biologists with a new robust source of precise quantitative information on the structure of terrestrial ecosystems, particularly canopy height and the stratification of vegetation between the canopy and ground surface. These are key attributes that define habitats and resource use for individual species (Figure 19) and have not been available at the regional to global scale. The fusion of LIDAR data with quad-pol radar data will allow ecologists to more precisely refine the spatial distribution of vegetation types, as well as the transitions among vegetation types that may be susceptible to the impact of global warming. Repeating measurements of radar continuously over the course of the year will provide information on the seasonal changes that influence the availability of resources and, consequently, the distribution of biodiversity at multiple scales.

4.1.4 Disturbance

Wildfires, meterological events, deforestation, desertification, and shrubification can all disturb forests and ecosystems. Scientists and natural resource managers will use information from DESDynI to quantify the impact of disturbance on natural ecosystems, such as wildfires and floods, as well as extreme events such hurricanes and droughts. The impact of human induced change will be monitored and quantified to produce objective estimates of the impact of land-use change, different forest management approaches, and the exploitation of mineral resources, among others.

4.2 Goals, Objectives, and Observation Needs

Characterize terrestrial ecosystems with respect to biomass, biodiversity, and disturbance/change through time.

4.2.1 Ecosystem Health and Management

DESDynI will facilitate the objective evaluation of the resiliency of globally important ecosystems, particularly the Amazon and Boreal forests. Specific questions to be answered include:

- Are these ecosystems sources or sinks of carbon?
- What is the spatial distribution of carbon fluxes and can they be linked to specific causal factors, such as disturbance (see below) or climate change?

Measurements will be global in scale and cover large areas where ground-based data may be scarce or non-existent. DESDynI will provide estimates of sufficient precision and accuracy to generate regional and local scale estimates of carbon pools and changes to those pools. Information derived from the mission will provide important societal benefit by providing objective baseline information of carbon stocks of the world's ecosystems and contribute to the development of international carbon markets by providing reliable and objective information regarding carbon pools and carbon fluxes.

4.2.2 Biodiversity

The DESDynI Mission will assist scientists in understanding the distribution of biodiversity at the global, regional and local scale. It will provide a baseline for monitoring the impact of global change on biodiversity, including ecosystem degradation from deforestation and other forms of land-use change, as well as natural resource extraction and global warming. Maps and GIS products derived from DESDynI data will be incorporated into models under development by conservation biologists to predict how species distributions might change due to climate change.

4.2.3 Disturbance

The five-year mission life should provide sufficient opportunity to document the scale and frequency of disturbance in different ecosystems, as well as the rate of recovery following disturbance. The global coverage of a LIDAR and quad-pol SAR fusion product could be combined with historical data from other sensors to identify a broader range of disturbance events and subsequent recovery trajectories.

The mission will provide substantial societal benefit by improving natural resource management and providing better information on land use and land-cover change. The combination of LIDAR and SAR over large geographic regions will provide a unique horizontal and vertical image of vegetation after natural or human disturbance. Better estimates of the scale and frequency of disturbance will inform real estate markets and the insurance industry, contributing to the protection of private property.

4.3 DESDynI Data Products and Required Ancillary Data

4.3.1 Ecosystem Health and Management

Assessment of ecosystem health and management of ecosystem resources requires an understanding of biomass and the vertical structure of forests. The principal data product would consist of a global map of aboveground live/dry biomass. Measurements are required that allow for the production of a map having a resolution of at least 250 meters, with 100 meters (1 hectare) being preferable. An accuracy of +/-10 Mg/ha (or 20%, whichever is greater) is preferred on an annual basis. A useful companion product to the biomass map would be a pixel-level map of prediction error. The biomass product has potential value across sub-disciplines, e.g., wildlife/biodiversity and disturbance mapping. For example, the mass of vegetation present in a given area can directly influence animal species distributions, rates of wildfire spread, evapotranspiration estimates, etc.

To produce a spatially explicit and accurate global biomass product, a number of ancillary data sources will be useful if not essential. Many of these data sources will also be required to meet the other ecosystem structure objectives described below. As such, a summary of these data sources will be included here in the context of biomass estimation and will not be covered elsewhere.

Perhaps the most important ancillary data source required for biomass estimation (as well as most other ecosystem structure applications) is ground reference data (i.e., ground-truth information). The development of robust empirical prediction models requires that ground reference data be: (1) statistically representative of observed biomass gradients, (2) temporally consistent with the sensor data, and (3) based on consistent measurement protocols. Existing forest inventories (e.g., FIA, FAO, etc.) tend to be the most consistent and accurate sources of ground reference data available, and will certainly prove valuable for calibration and validation activities.

It is important to recognize that most traditional forest inventory information is not well suited for integration with remotely sensed information, i.e., traditional forestry measurement protocols were not designed with remote sensing applications in mind. Hence, attempts to rely heavily on existing, disparate inventory data sources should be discouraged. In planning for this mission, NASA should give serious consideration to new regional-to-continental ground measurement campaigns as this is the only way that field measurements can be truly optimized for integration with remotely sensed information. It is also the only way high-quality products can be produced.

These campaigns should be coordinated with ongoing efforts to study the dynamics of forest ecosystems, most of which are implementing updated protocols to monitor carbon fluxes and to document how these changes are affecting biodiversity. Specifically, NASA should pursue alliances with the National Ecological Observatory Network (NEON), which is suppoitrted by NSF, the Amazonian Forest Inventory Network

(RAINFOR), which is a legacy of NASA's LBA program, and the Smithsonian's Center for Tropical Forest Science (STRI/CTFS). (see Figure for spatial distribution of these networks)

NEON: http://www.neoninc.org
RAINFOR: http://www.geog.leeds.ac.uk/projects/rainfor/
CTFS: http://www.ctfs.si.edu

It is also important to recognize the limitations associated with the use of existing allometric equations for converting ground measurements, e.g., stem diameters, heights, etc., to above-ground biomass. Although allometric equations are critical to the empirical estimation of biomass, there remains room for much improvement globally in these equations.

In addition to the obvious need for field data where biomass estimation and other ecosystem structure applications are concerned, additional valuable ancillary data sources include: (1) optical imagery (MODIS, Landsat, Quickbird, aerial photography, etc.) for fusion and/or calibration/validation purposes, (2) historical image data sources (JERS, ALOS/PALSAR, etc.) for long-term change investigations, and (3) digital elevation model data and derivatives of slope/aspect for fusion, orthorectification, etc.

Overall, ancillary data, and particularly the availability of ground-reference data, should be considered essential to meeting many if not all ecosystem structure objectives. Without these ancillary data sources, the accuracy of most data products will be seriously diminished and their applications limited.

4.3.2 Biodiversity

Several data products will potentially meet the needs of the biodiversity/wildlife community. Perhaps the most desired product is a global map of vegetation canopy height. Ideally such a map would be produced annually at a resolution of 100 meters or higher with a vertical accuracy of circa 1 meter. A second data product of interest is a global map of vertical structural complexity. Vertical structural complexity is defined here as the number of semi-discreet vertical canopy layers, i.e., canopy, subcanopy, understory/shrub, etc.). The product(s) could contain information on (1) the number of observed canopy layers present and/or (2) the vertical height associated with each observed layer. A resolution of 100 meters and a vertical accuracy of 1 meter are desired. Additional useful global products for biodiversity/wildlife applications include height to live crown, and height of median canopy energy.

4.3.3 Disturbance Mapping

A desirable product under the category of disturbance mapping would include an annually/semi-annually produced map of vegetation cover (e.g., forest, shrub, transitional vegetation), that could be used to assess vegetation change (i.e., resulting from natural and/or anthropogenic disturbance) over the course of the mission. Although there are many data products available for monitoring deforestation and other forms of land-use change, there are no adequate protocols using remote sensing data for monitoiring forest degradation, which was recently defined by the UNFCCC (COP-13) as any forest that has experienced a loss of. Thus objective estimates of temporal changes in biomass are of increasing importance to society. Less applied users will prefer and should have access to Level 1/2 SAR backscatter/coherence products with which to conduct their own disturbance-related analyses.

4.4 Monitoring and Event Response Plan

4.4.1 Ecosystem Health and Management

Global biomass measurements are to be achieved through continuous monitoring with quad pol SAR and LIDAR over all vegetated regions of the Earth. Recent research suggests that InSAR could be a valuable tool in estimating crown height, to be used as a proxy for biomass. However, if orbital control is optimized for deformation studies (i.e. zero baseline), InSAR will not be a viable option for tree height measurement. Instead, biomass measurements will rely on SAR polarimetry (PolSAR) fused with LIDAR.

Continuous acquisition with quad pol SAR will offer the best means to capture the seasonal variability of the ecosystems. Leaf-on, leaf-off, snow-covered, dry, and inundated acquisition conditions all yield important information on tree type, 3-dimensional (3D) structure, and environment. By obtaining continuous SAR observations, we obviate the need for complex tasking plans that in hindsight may not yield optimal results.

The starting point for derived SAR products will be Single Look Complex (SLC) quad pol data. This level will permit full flexibility with respect to various polarimetric decompositions and analysis, and may become the basis for higher-level products that may be produced on an as-requested basis. For forests with biomass less than 100 Mg/Ha, this strategy of fusing quad pol and LIDAR data should be adequate. (Some assessment of accuracy should be inserted here). However, for denser vegetation, saturation of the backscattered signal from volumetric scattering will pose a limitation for SAR observations. In this case, we will be reliant upon LIDAR for biomass estimation. LIDAR, by its acquisition strategy, will offer only incomplete global coverage, even after five years. However it will provide invaluable information on structure, biomass, and statistical variability within high biomass forests.

Ecosystem health and management is becoming important to an expanding set of international agencies and researchers. Biomass assessment will become even more important with the implementation of a carbon market based on reducing carbon from deforestation. Unlike emergency response, where time critical information must be vectored to responsible agency in near-real time, the SLC and derived products for biomass estimation must simply be made available for download as needed. Since the data are not of a time-critical nature, desired latencies are on the order of days or weeks.

4.4.2 Biodiversity

It is anticipated that neither SAR nor LIDAR will be capable of assessing either vegetation or animal biodiversity. However, both will provide useful information for quantifying landscape heterogeneity, particularly the existence and integrity of habitat corridors and habitat fragmentation, landscape attributes that are often important for the conservation of biodiversity. LIDAR is especially suited to inferring biodiversity by providing 3-D vegetation structure, which can be related to habitat complexity, a key attribute for predicting species diversity (often referred to as alpha diversity). LIDAR, in conjunction with models that stratify different vegetation types will provide information on habitat type and the spatial variability of habitat type (often referred to as beta diversity). Information on vegetation type (as a surrogate for habitat) can be used to estimate animal biodiversity using models that relate differences in vegetation complexity to the number of anumal species.

4.4.3 Disturbance Mapping

It is expected that SAR coherence plots will be a useful tool for monitoring ecosystem disturbances. By measuring correlations between successive SAR scenes, disturbances associated with fire, deforestation, meteorological events, infestations, and ecosystem transition can be observed. Here the sampling requirement of continuous SAR measurements will facilitate catching significant disturbances as they occur and provide the means for monitoring recovery.

The sampling strategy with LIDAR varies significantly from that of SAR. The coverage is sparse, yielding only a sampled grid over the mission lifetime. Without repeat observations, it will not be capable of catching or monitoring disturbances. However, if a disturbance event is observed through alternative means, LIDAR may be tasked to revisit a previously viewed site or to cover a location that has not been viewed. Thus, LIDAR tasking can be used to achieve one of two goals: (1) produce repeat acquisitions for monitoring recovery from disturbance, or (2) achieve a denser data grid than will be achievable through the nominal sampling strategy. It should be understood that tasking the LIDAR instrument has consequences: (1) it cannot achieve an exact repeat measurement (only within 10 meters) and (2) it reduces the number of samples in the LIDAR global grid.

4.5 Targets and Observational Frequency

The observation target for forest and ecosystem management is the global distribution of vegetated surfaces, including the surrounding transition zones required to capture encroachment or degradation. Non-vegetated surfaces are defined as non-productive deserts, bare rock, perennial ice and snow covered regions, and open water. For the most part, each of the subsections below depends on a global observation strategy, requiring the instruments to observe global vegetation continuously. Phenological variations within a given ecosystem may be captured by observing a small number of seasonal vegetative states, but the variability between ecosystems precludes a single seasonal sampling strategy on a global basis. There are special observation needs for “super sites” required for calibration and validation purposes. For example, more frequent LIDAR observations may be required to achieve a higher spatial sampling that the nominal 250m achievable over a year. However, the group determined that global monitoring needs override targeting specific events, given that the occurrence and impacts of various types of disturbance will likely be captured by a continuous observation strategy with other sensors.

For SAR observations, quad-polarization measurements are required to adequately determine biomass over a range of ecosystems. Under the current acquisition scenario, this would require 48 days to acquire quad-polarizations measurements along a given track. However, the possibility of a “sweep-SAR” mode may permit 8-day repeat coverage globally. Discussions centered on the use of dual-polarization scanSAR mode for 8-day repeat coverage; however, the group believes mathematical formalism for retrieving biomass is lacking for dual-polarization measurements. In addition, SAR backscattering intensities alone are inadequate to estimate biomass globally, due to saturation of the SAR signal at ~100 Mg/ha.

The first year of observations during the 5-year mission will be used to establish a baseline for algorithm evaluation, product validation and disturbance mapping. The first year’s observations permit the accumulation of statistics and model errors necessary to refine processing algorithms and analytical methods in subsequent years. The first year will also provide a reference for disturbance mapping over the life of the mission. Finally, a critical exercise to be completed during the first year is the development of sampling protocols and identification of calibration and validation test sites required to reconcile and cross-validate carbon stock inventories from different agencies and countries to normalize the inventories derived using different methods.

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Appendix A: Workshop Attendees

Name	Affiliation
Dr. Shyam N. Bajpai	NOAA/NESDIS/OSD
Andrea Donnellan	Jet Propulsion Laboratory, California Institute of Technology
Louise Kellogg	University of California, Davis
Donald L. Turcotte	UC Davis
Badie Rowshandel	California Geological Survey and California Earthquake Authority
Nettie La Belle-Hamer	Alaska Satellite Facility
Irena Hajnsek	German Aerospace Center
Don Vasco	Berkeley Lab
Michael Eineder	DLR
Elijah Ramsey III	US Geological Survey
Jeanne Sauber	NASA Goddard Space Flight Center
John Rundle	University of California
Robert C. Smith	NASA
Craig Dobson	NASA HQ
David Meyer	USGS/EROS
Stephen Volz	NASA HQ
Gerald Bawden	US Geological Survey
David Sandwell	UCSD/SIO
Brian Huberty	U.S. Fish & Wildlife Service
Susan Schoenung	Bay Area Environmental Research Institute
Scott Hensley	JPL
Cathleen Jones	Jet Propulsion Laboratory
Paul Rosen	Jet Propulsion Laboratory
Zhong Lu	US Geological Survey
Charles Real	California Geological Survey
Benjamin Holt	JPL
Frank Monaldo	Johns Hopkins APL
Michelle Sneed	U.S. Geological Survey
Stephen Ambrose	NASA HQ
Nicholas B. Woodward	Department of Energy
Peter Cervelli	U.S. Geological Survey
William Pichel	NOAA/NESDIS/Center for Satellite Applications and Research

Bradford H. Hager	MIT
Jay Parrish	AASG - PA Geological Survey
Ronald G Blom	JPL
Carolyn Hunsaker	USDA Forest Service, Research
John C. Eichelberger	US Geological Survey
Matthew Fladeland	NASA Ames Research Center
Dr. Roy K. Dokka	
Len Gaydos	USGS
Timothy J. Killeen	Conservation International
Steve Ingebritsen	U.S. Geological Survey
Robert Anderson	Alfred E. Alquist Seismic Safety Commission
William R. Emanuel	NASA Headquarters
Larry Myer	Lawrence Berkeley National Laboratory
Charles Meertens	UNAVCO
Ben Brooks	SOEST University of Hawaii
Wayne Walker	Woods Hole Research Center
Gretchen Moisen	US Forest Service - FIA
Herman H. Shugart	University of Virginia
Lauren Nakashima	UC Davis
Sean Buckley	University of Texas at Austin
Mark Folkman	Northrop Grumman
Frederick Policelli	NASA GSFC
Jason Stoker	USGS EROS
SHAWN MURPHY	C.S. DRAPER LABORATORY
Lee Allison	Arizona Geological Survey
Maria Sotero	New America Foundation
Jennifer Dungan	

Appendix B: Workshop Breakout Sessions and Questions

Applications in the Context of DESDynI

DESDynI can provide unique observations of surface deformation and ecosystem structure. It can also be used to provide imagery for various events such as floods or wildfires. Workshop attendees were asked to respond to the following questions:

8. What are the specific specifications and objectives for each application?
9. Specifically what return will DESDynI provide for the application?
10. Do the DESDynI instruments provide unique measurements for meeting the objectives?
11. Is the application consistent with goals of the Decadal Survey?
12. How does this integrate with the Global Earth Observing System of Systems (GEOSS) goals and the grand challenges from the Subcommittee on Disaster Reduction? Do these fit a gap in those reports?

Goals, Objectives, and Observation Needs

1. What is the goal to be achieved with DESDynI observations for each specific application? These need to be guided by the decadal survey.
2. What are the societal benefits? Are there quantitative metrics?
3. What are the specific objectives for each specific application?
4. What are the observation needs?

   a. What parameter[s] will be measured or quantified?

   b. What resolution is needed?

   c. What accuracy or precision is needed?

   d. Are their other constraints

   Temporal and coverage constraints were addressed in Breakout V

5. What study, report, or other analysis led to the needs?

DESDynI Data Products and Required Ancillary Data

6. What specific data products does DESDynI need to produce to meet the goals and objectives for each application?
7. What additional supporting or ancillary data are required to meet the stated objectives?

8. Quantitatively how much will the objectives be met with availability of the ancillary data?

9. Can the objectives be met without those ancillary data?

Monitoring and Event Response Plan

10. How soon after an event must a region be surveyed with DESDynI?

11. What types of measurements and observations are needed?

12. What data products are needed?

13. What ancillary measurements and data are required?

14. How will the data be disseminated and to what agencies?

15. What is the latency required for the data to be useful?

Targets and Observational Frequency

16. What are the specific geographic targets for each discipline?

17. How often do these targets need to be measured?

    a. Weekly?

    b. During the growing season?

    c. Yearly?

18. Are there baseline measurements that need to be made at the beginning and the end of the mission?

19. What targets are absolutely necessary and what targets are desired? There will be limitations on the spacecraft and downlink.

20. What data products are needed?